Proposal for the origin of the cosmological constant

Roberto Dale*

Departamento de Física,

Ingeniería de Sistemas y Teoría de la Señal,

Universidad de Alicante, 03690,

San Vicente del Raspeig, Alicante, Spain

Juan Antonio Morales–Lladosa and Diego Sáez†

Departamento de Astronomía y Astrofísica,

Universidad de Valencia,

46100 Burjassot, Valencia, Spain

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Abstract

We work in the framework of a simple vector-tensor theory. The parametrized post-Newtonian approximation of this theory is identical to that of general relativity. Our attention is focused on cosmology. In an homogeneous isotropic universe, it is proved that the energy density, $\rho_{_A}$, of the vector field A, and its pressure, $p_{_A}$, do not depend on time, and also that the equation of state is $\rho_{_A} = -p_{_A}$. This means that, in the theory under consideration, there is a cosmological constant, which is not vacuum energy, but the dark energy of the cosmic vector field A, whose evolution is classical.

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*Electronic address: rdale@dfists.ua.es

†Electronic address: antonio.morales@uv.es; diego.saez@uv.es

I. INTRODUCTION

We begin with our motivations to study vector-tensor theories. As it is well known, the analysis of the WMAP (Wilkinson microwave anisotropy probe) data has pointed out a set of anomalies in the cosmic microwave background (CMB) angular power spectrum, e.g., the planar character of the octopole and its alignment with the quadrupole, [1, 2, 3, 4, 5] the asymmetry between the north and south ecliptic hemispheres [6, 7, 8, 9, 10], and so on. These anomalies strongly suggest that the distribution of CMB temperatures deviates from statistical isotropy at very large angular scales. Most of these anomalies have been recently explained [11] by using divergenceless peculiar velocities (superimpositions of the so-called vector modes) in the framework of general relativity (GR); nevertheless, in this theory, the angular velocity of these divergenceless motions decays during the matter dominated era and, consequently, such motions should be generated close to $z = 1100$ to produce CMB anisotropy after decoupling and before decaying [11, 12]. This condition seems to be necessary to make possible the explanation of the low ℓ CMB anomalies proposed in [11]; nevertheless, no specific processes are known to create the required divergenceless velocity fields around $z = 1100$. By this reason, we propose the use of some suitable theory involving more vector modes than GR. In this alternative theory, the evolution of the angular velocity could be very different and more appropriate to explain anomalies. These comments suggest the choice of some vector-tensor theory, whose four-vector field leads to new vector modes associated to its spatial part. According to these ideas, we are performing a study of the vector-tensor theories obtained from the Lagrangian described in the next section [13]. Other theories will be considered in the future. Our first outcomes on the evolution of vector modes in vector-tensor theories were presented in [14].

Before studying the evolution of the vector modes in a given vector-tensor theory, we should explain some well known observations; e.g., it should have an appropriate parametrized post-Newtonian (PPN) limit compatible with solar system observations. In a first step, we are studying some vector-tensor theories leading to the same PPN parameters as GR. Moreover, in the chosen theory, the homogeneous and isotropic cosmological background should explain, at least, all the observations already explained by the concordance model. The main goal of this paper is the description of a theory with these characteristics. We have found one of them, in which the vector field plays the role of the cosmological constant. No vacuum energy is then needed to explain $SN\ Ia$ observations, CMB anisotropies, baryonic acoustic oscillations, and so on. These surprising results have motivated this brief paper.

We think that the new classical origin of the cosmological constant is a very interesting result. It deserves attention even if CMB anomalies cannot ever be explained in the framework of the selected vector-tensor theory. The evolution of the vector modes (perturbations of the background four-vector used here) is not required in this paper. It is necessary to try to explain anomalies (our initial motivation), but this possible explanation is yet to be studied. Results will be presented elsewhere.

In this paper, G, a, τ, and z stand for the gravitation constant, the scale factor, the conformal time, and the redshift, respectively. Greek (Latin) indexes run from 0 to 3 (1 to 3). Whatever function ξ may be, $\xi^{\star}$ is its present value and $\dot{\xi}$ (ξ') denotes its partial derivatives with respect to τ (z). Quantity ρ_c is the critical density, ρ_r (ρ_m) is the radiation (matter) energy density, and $\rho_b = \rho_r + \rho_m$ is the total background energy density of the cosmological fluid. Since we work in a flat universe, the present value of the scale factor $a^{\star}$ is assumed to be unity and, then $a = (1+z)^{-1}$. Quantity w is the ratio between pressure p and density ρ. Units are defined in such a way that the speed of light is $c = 1$. Finally, indexes are raised and lowered with the space-time metric.

II. VECTOR-TENSOR THEORIES

In GR, there is a tensor field $g_{\mu\nu}$ which plays the role of the space-time metric. In the vector-tensor theories, there are two fields, the metric $g_{\mu\nu}$ and a four-vector A^{μ}. Several of these theories have been proposed (see [13], [15] and references cited there). We have first considered those based on the action [13]:

$$I = (16\pi G)^{-1} \int (R + \tilde{\omega} A_{\mu} A^{\mu} R + \tilde{\eta} R_{\mu\nu} A^{\mu} A^{\nu} - \tilde{\varepsilon} F_{\mu\nu} F^{\mu\nu} + \tilde{\gamma}\, \nabla_{\nu} A_{\mu} \nabla^{\nu} A^{\mu} + L_m) \sqrt{-g}\, d^4x \tag{1}$$

where $\tilde{\omega}$, $\tilde{\eta}$, $\tilde{\varepsilon}$, and $\tilde{\gamma}$ are arbitrary parameters, R, $R_{\mu\nu}$, g, and L_m are the scalar curvature, the Ricci tensor, the determinant of the $g_{\mu\nu}$ matrix, and the matter Lagrangian, respectively. The symbol ∇ stands for the covariant derivative, and $F_{\mu\nu} = \nabla_{\mu} A_{\nu} - \nabla_{\nu} A_{\mu}$. In action (1), it is implicitly assumed that the coupling between the matter fields and A_{μ} is negligible. A more general action is given in [15]. It involves a new term of the form $\lambda(A_{\mu} A^{\mu} + 1)$, where λ is a Lagrange multiplier. With the help of this term, the vector A^μ is constrained to be timelike with the unit norm. From this last action, the field equations of the so-called Einstein-Aether constrained theories can be easily obtained. The applications of these theories to cosmology are discussed, e.g., in [16]. A mass term of the form $m_{_A}^2 A_\mu A^\mu$ is used in [17] to explain cosmic acceleration with a massive vector field. The same is done in [18] for an unconstrained theory based on action (1). Recently, other theories involving vector fields have also been applied to cosmology (see, e.g., [19, 20]). Fortunately, among all the proposed vector-tensor theories, we have found a simple unconstrained one, based on the action (1), which leads to a new interpretation of the concordance model in the absence of vacuum energy.

It can be easily proved that, for $\tilde{\omega} = 0$, $\tilde{\eta} = \tilde{\gamma}$, and arbitrary $\tilde{\varepsilon}$, the PPN parameters of the theory based on the action (1) are identical to those of GR [13], [21]. For this choice of the free parameters we easily get the following field equations (see [13]):

$$\tilde{\eta}\,(\nabla_\nu \nabla^\nu A_\mu - R_{\mu\nu} A^\nu) + 2\tilde{\varepsilon}\,\nabla^\nu F_{\mu\nu} = 0 \tag{2}$$

$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu} + \tilde{T}^A_{\mu\nu}\ , \tag{3}$$

where $G_{\mu\nu}$ is the Einstein tensor, $\tilde{T}^A_{\mu\nu} = -\tilde{\eta}[\Theta^{(\tilde{\eta})}_{\mu\nu} + \Theta^{(\tilde{\gamma})}_{\mu\nu}] - \tilde{\varepsilon}\Theta^{(\tilde{\varepsilon})}_{\mu\nu}$, and the explicit form of $\Theta^{(\tilde{\eta})}_{\mu\nu}$, $\Theta^{(\tilde{\gamma})}_{\mu\nu}$, and $\Theta^{(\tilde{\varepsilon})}_{\mu\nu}$ is given in [13]. Taking into account the identity

$$\nabla_\alpha \nabla_\beta A^\alpha - \nabla_\beta \nabla_\alpha A^\alpha = R_{\alpha\beta} A^\alpha\ , \tag{4}$$

Eq. (2) is easily rewritten in the form:

$$\tilde{\eta}\nabla_\mu(\nabla \cdot A) + (2\tilde{\varepsilon} - \tilde{\eta})\nabla^\nu F_{\mu\nu} = 0\ , \tag{5}$$

where $\nabla \cdot A = \nabla_\alpha A^\alpha$. By using the identity (4) and Eq. (5), the energy-momentum tensor of the field A_μ; namely, the tensor $T^A_{\mu\nu} = \tilde{T}^A_{\mu\nu}/8\pi G$ can be written as follows:

$$\begin{aligned} T^A_{\mu\nu} \ =\ & \Big[-\frac{\eta}{2}(\nabla \cdot A)^2 + (2\varepsilon - \eta)\Big(A^\alpha \nabla^\beta F_{\alpha\beta} - \frac{1}{4} F_{\alpha\beta} F^{\alpha\beta}\Big)\Big] g_{\mu\nu} \\ & + (2\varepsilon - \eta) g^{\alpha\beta} \Big(F_{\mu\alpha} F_{\nu\beta} + A_\mu \nabla_\beta F_{\nu\alpha} + A_\nu \nabla_\beta F_{\mu\alpha}\Big)\ ; \end{aligned} \tag{6}$$

where $\eta = \tilde{\eta}/8\pi G$, and $\varepsilon = \tilde{\varepsilon}/8\pi G$. Finally, in the cosmological case, $T_{\mu\nu}$ is the energy-momentum tensor of the cosmological fluid, which involves both matter and radiation. It is worthwhile to notice that the relation

$$\nabla^\mu T^A_{\mu\nu} = 0 \tag{7}$$

is satisfied (see [13]) and, consequently, taking into account Eq. (3) and the identity $\nabla^{\mu} G_{\mu\nu} = 0$, the relation $\nabla^{\mu} T_{\mu\nu} = 0$ is also satisfied. This means that matter and radiation evolve as in the standard Friedmann-Robertson-Walker model of GR and, as it is well known, after the $e^{\pm}$ annihilation, which took place at $z \sim 10^{10}$ (see [22]), the following equations are valid: $3p_r = \rho_r = \rho_r^{\star}(1+z)^4$, $\rho_m = \rho_m^{\star}(1+z)^3$, and $p_m \simeq 0$.

For $\tilde{\omega} = \tilde{\eta} = \tilde{\gamma} = 0$ and $\tilde{\varepsilon} \neq 0$, the term $-\tilde{\varepsilon} F_{\mu\nu} F^{\mu\nu}$ involved in the action (1) has the same form as the term appearing in the action of an electromagnetic field in the absence of sources. In this case, Eq. (5) reduces to $\nabla^{\nu} F_{\mu\nu} = 0$ and the energy-momentum tensor of the field A_{μ} is $T^{A}_{\mu\nu} = 2\varepsilon[g^{\alpha\beta} F_{\mu\alpha} F_{\nu\beta} - (1/4) g_{\mu\nu} F_{\alpha\beta} F^{\alpha\beta}]$. As it is well known, the field A_{μ} is called the potential vector of $F_{\mu\nu}$. The equations of the theory can be written in terms of the field $F_{\mu\nu}$ and its derivatives and, consequently, classical theoretical predictions and observations refer only to the field $F_{\mu\nu}$. Some indetermination in the potential field A_{μ} is unavoidable (the potential vector can be arbitrarily fixed by using appropriate gauge conditions). Similarly, for other values of the parameters involved in the action (1), the vector field A_{μ} may also play the role of a potential generating other measurable physical fields involved in the field equations. The role of vector A_{μ} and the indetermination in it depend on the properties of the Lagrangian (invariance under transformations of A_{μ}). For example, in the case $\tilde{\omega} = 0$, $\tilde{\eta} = \tilde{\gamma}$, and $2\tilde{\varepsilon} = \tilde{\eta} \neq 0$, the energy-momentum tensor reduces to $T^{A}_{\mu\nu} = -\frac{\eta}{2}(\nabla \cdot A)^2 g_{\mu\nu}$ and Eq. (5) gives $\nabla_{\mu}(\nabla \cdot A) = 0$. According to this last equation $\nabla \cdot A$ is constant and, consequently, tensor $T^{A}_{\mu\nu}$ has the same form as the energy-momentum tensor corresponding to vacuum; namely, one has $T^{A}_{\mu\nu} = -\rho_{A} g_{\mu\nu}$, where $\rho_{A} = \frac{\eta}{2}(\nabla \cdot A)^2 = constant \neq 0$. This means that the resulting theory is equivalent to GR plus a cosmological constant. In this theory, A_{μ} is not a classical field to be determined either with the field equations or with observations, it is a field playing the role of a potential vector for the scalar field $\nabla \cdot A$, which is the only field (apart from the metric) involved into the field equations of the theory.

In this paper, we pay particular attention on the theory corresponding to $\tilde{\omega} = 0$, $\tilde{\eta} = \tilde{\gamma} \neq 0$, and $0 \neq 2\tilde{\varepsilon} \neq \tilde{\eta}$. For this choice of the free parameters of the action (1), the field equations (see above) are more complicated than in the simple case $2\tilde{\varepsilon} = \tilde{\eta}$; for example, according to Eq. (5), the scalar $\nabla \cdot A$ is not constant, excepting some special physical systems as, e.g., a homogeneous and isotropic background universe. The evolution of the cosmological background is studied in the next sections.

III. COSMOLOGY: BASIC EQUATIONS AND COSMOLOGICAL CONSTANT

In this section, we focus our attention on a homogeneous and isotropic cosmological background. In the flat case, the line element is

$$ds^2 = a^2(-d\tau^2 + \delta_{ij} dx^i dx^j) \ . \tag{8}$$

Moreover, homogeneity and isotropy require a vector field whose covariant components are $(A_0(\tau), 0, 0, 0)$. Then, tensor $F_{\mu\nu}$ vanishes and

$$\nabla \cdot A = -\frac{1}{a^2} \left(\dot{A}_0 + 2\frac{\dot{a}}{a} A_0 \right) \ ; \tag{9}$$

hence, Eq. (5) reduces to the relation $d(\nabla \cdot A)/d\tau = 0$, which can be rewritten in the form:

$$\ddot{A}_0 + 2A_0 \left(\frac{\ddot{a}}{a} - 3\frac{\dot{a}^2}{a^2} \right) = 0 \ . \tag{10}$$

Equation (6) allows us to find the components of $T^A_{\mu\nu}$. By using these components, Eqs. (3) can be written as follows:

$$3\frac{\dot{a}^2}{a^2} = 8\pi G a^2 (\rho_b + \rho_A) \tag{11}$$

and

$$-2\frac{\ddot{a}}{a} + \frac{\dot{a}^2}{a^2} = 8\pi G a^2 (p_b + p_A) \ , \tag{12}$$

where

$$\rho_A = -p_A = \frac{\eta}{2}(\nabla \cdot A)^2 = \frac{\eta}{2a^4} \left(\dot{A}_0 + 2\frac{\dot{a}}{a} A_0 \right)^2 \ ; \tag{13}$$

hence, $w_A = -1$, as it occurs in the case of the cosmological constant ($w_\Lambda = -1$).

Since we have found that —in the cosmological case— the energy-momentum tensor of the field A has the form

$$T^A_{\mu\nu} = -\rho_A g_{\mu\nu} \ , \tag{14}$$

Eq. (7) implies the relation $\dot{\rho}_A = 0$; hence, the energy density ρ_A is constant. This is in agreement with the relations $\rho_A = \frac{\eta}{2}(\nabla \cdot A)^2$ and $d(\nabla \cdot A)/d\tau = 0$ previously obtained.

Evidently, if the energy density of the evolving field A is constant and the relation $\rho_A = -p_A$ is satisfied, we can state that this field acts as a cosmological constant. The possible values of ρ_A are discussed in the next section.

IV. SOLVING THE BASIC COSMOLOGICAL EQUATIONS

In order to integrate Eqs. (10)–(12), the following new variables are appropriate: $\zeta = 1+z$, $y_1 = \tau'$, $y_2 = A_0$, and $y_3 = A'_0$. In terms of these variables, the energy density is

$$\rho_{_A} = \frac{\eta\zeta^2}{2y_1^2}(y_3\zeta - 2y_2)^2 \ , \tag{15}$$

and Eq. (11) can be rewritten as follows:

$$\eta\zeta^2(y_3\zeta - 2y_2)^2 + 2y_1^2\zeta^3\left(\zeta\rho_r^\star + \rho_m^\star\right) = \frac{3}{4\pi G} \ , \tag{16}$$

whereas Eq. (12) leads to

$$y'_1 = -\frac{y_1}{6\zeta}\left\{4\pi G\zeta^2\left[2y_1^2\rho_r^\star\zeta^2 - 3\eta(y_3\zeta - 2y_2)^2\right] + 9\right\} \ . \tag{17}$$

Finally, the second order differential equation (10) leads the following system of first order equations:

$$y'_2 = y_3 \tag{18}$$

and

$$y'_3 = \frac{2y_2y_1 + y'_1\zeta\left(y_3\zeta - 2y_2\right)}{y_1\zeta^2} \tag{19}$$

From Eqs. (16) and (17) one easily finds

$$\frac{y'_1}{y_1^3} = -\frac{4\pi G}{3}(4\rho_r^\star\zeta^3 + 3\rho_m^\star\zeta^2) \ , \tag{20}$$

which can be easily integrated to get

$$y_1 = -\left[\frac{3}{8\pi G(\rho_r^\star\zeta^4 + \rho_m^\star\zeta^3 + C)}\right]^{1/2} \ . \tag{21}$$

By combining Eqs. (15), (16), and (21) we can easily get the equality $C = \rho_{_A}$; therefore, taking into account that C is an arbitrary integration constant, the constant $\rho_{_A}$ can take on any value and, in particular, we can fix the value $\rho_{_A} = \rho_{_A}^\star = \rho_c^\star - \rho_m^\star - \rho_r^\star$ and $\rho_m^\star \simeq 0.27\rho_c^\star$; thus, we will have a flat universe with a cosmological constant whose density parameter is $\Omega_{_A} \simeq 0.73$ and, consequently, we can say that we have got a model explaining the same observations as the concordance model. In the new model, the dark energy is not vacuum energy, but the energy of the A field. Since the $\rho_{_A}$ value has been fixed, and the relation $C = \rho_{_A}$ is satisfied, Eq. (21) fully defines the function $y_1 = y_1(\zeta)$, which can be substituted into Eq. (19) to solve the system formed by this equation and Eq. (18). In order to find a numerical solution of this system, the initial values of y_2 and y_3 are necessary. We have taken $z_{in} = 10^8$ to be well inside the radiation dominated era and after $e^{\pm}$ annihilation. As it is well known, in this era, the scale factor is proportional to the conformal time; hence, one can write $a = \alpha\tau$, where α is a constant. Moreover, close to z_{in}, the component A_0 will be approximately proportional to some power of τ, namely, $A_0 = \beta\tau^\delta$. If these power laws are substituted into Eq. (10), we obtain the relation $\delta^2 - \delta - 6 = 0$, whose solution $\delta^+ = +3$ ($\delta^- = -2$) defines a growing (decaying) mode. We then use the growing mode $A_0 = \beta^+\tau^3$ plus the relation $\tau = (\alpha\zeta)^{-1}$ to get the following initial values for the variables y_1, y_2, and y_3:

$$y_{1in} = -\alpha^{-1}\zeta_{in}^{-2}; \quad y_{2in} = \beta^+\alpha^{-3}\zeta_{in}^{-3}; \quad y_{3in} = -3\beta^+\alpha^{-3}\zeta_{in}^{-4} \ . \tag{22}$$

Since $\rho_{_A}$ is constant, its value can be calculated from the initial conditions (22) and Eq. (15). The resulting formula is

$$\rho_A = \frac{25\eta(\beta^+)^2}{2\alpha^4} \tag{23}$$

The initial conditions necessary to solve Eqs. (18) and (19); namely, quantities y_{2in} and y_{3in} are given by Eqs. (22), but we need the explicit values of the constants α and β^+. In order to get these constants, we proceed as follows: since y_{1in} has been already calculated, the first of Eqs. (22) allows us to obtain $\alpha = -y_{1in}^{-1}\zeta_{in}^{-2}$ and, then, from the known values of α and $\rho_{_A}$, plus Eq. (23), we get $\beta^+ = \pm\alpha^2(2\rho_{_A}/25\eta)^{1/2}$; hence, parameter η is arbitrary, but it only can take on positive values. After fixing η, there are two β^+ values with the same absolute value and opposite signs. Each of these values generates a set of initial conditions. Indeed, in Eq. (23), it is easily seen that the value of $\rho_{_A}$ (estimated to explain the observations, see above) fixes the product $(\beta^+)^2\eta$, but the η value and the sign of β^+ remain arbitrary.

It is evident that, if functions $y_2(\zeta)$ and $y_3(\zeta)$ satisfy Eqs. (18) and (19), and D is an arbitrary constant, functions $Dy_2(\zeta)$ and $Dy_3(\zeta)$ also satisfy these equations. Moreover, according to Eqs. (22), quantities y_{2in} and y_{3in} are proportional to β^+, which means that, if we find the numerical solution of Eqs. (18) and (19) for $\beta^+ = \alpha^2(2\rho_{_A}/25)^{1/2}$ (this positive β^+ value corresponds to $\eta = 1$), the products of the resulting functions $y_2(\zeta)$ and $y_3(\zeta)$ by $D = \pm 1/\eta^{1/2}$ give other solution. We can thus obtain the solution corresponding to any η value and β^+ sign.

The A_0 function corresponding to $\beta^+ = \alpha^2(2\rho_{_A}/25)^{1/2}$ is given in Fig. 1 (in terms of variable ζ). Equation (16) can be seen as a constraint which must be satisfied by functions y_1, y_2 and y_3. We have verified that the functions we have obtained in our numerical integration satisfy this equation with a relative error $(\Xi_1 - \Xi_2)/\Xi_2$ smaller than 2×10^{-12} for any z, where Ξ_1 (Ξ_2) is the value of the left- (right-) hand side of Eq. (16). This is a satisfactory numerical test for our numerical methods and calculations. Very similar results have been obtained with various numerical methods designed to the integration of systems of first order differential equations.

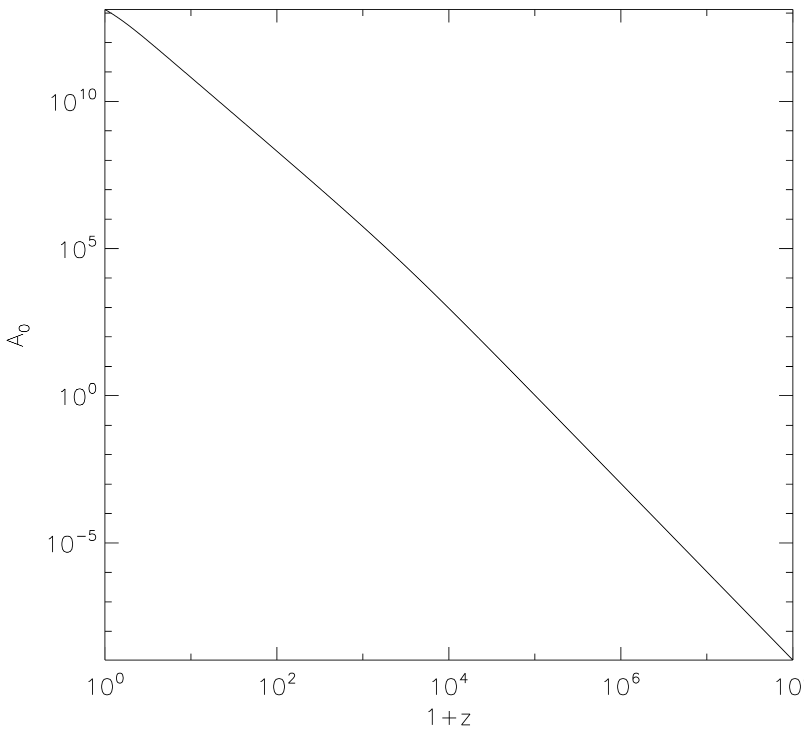

FIG. 1: A_0 component of the four-vector A as a function of $1+z$, for $\eta = 1$ and positive β^+.

V. GENERAL DISCUSSION

In the concordance model, we have baryonic matter, dark matter, and vacuum energy in well-known proportions. The problem with vacuum energy is that theoretical predictions —based on standard quantum field theory— lead to very big values of this kind of energy, which are not compatible with those required to explain current observation (this is the so-called cosmological constant problem). We might imagine some new quantum theory leading to a strictly vanishing vacuum energy, but a good enough fitting to the particular value $0.73\rho_c^\star$ seems to be a fine tuning; however, the vector field A_μ is not normalized either by theoretical arguments or by non-cosmological observations, which means that, if this field exists in nature, cosmological data ($\rho_{_A}$ value) may be used, as it is done in previous section, to succeed in the required normalization. On account of these comments, the new origin for the cosmological constant seems to be very good news.

In this paper we have proved that a certain cosmic field A, with an appropriate Lagrangian, can play the role of the gravitational constant. This field is coupled to the scalar curvature and the Lagrangian have the following form:

$$\mathcal{L} = \frac{R}{16\pi G} + \frac{\eta}{2}\left[R_{\mu\nu}A^\mu A^\nu \, + \, \nabla_\nu A_\mu \nabla^\nu A^\mu\right] - \frac{\varepsilon}{2} F_{\mu\nu}F^{\mu\nu} \ . \tag{24}$$

The constant energy density $\rho_{_A}$ can take on the right value ($0.73\rho_c^\star$) whatever the values of the η and ε parameters may be. Component A_0 evolves (see Fig. 1 and Sec. IV), but $\rho_{_A}$ is constant and the relation $w_{_A} = -1$ is valid at any time. The resulting model is fully equivalent to the standard concordance model.

The new version of the cosmological constant appears in the study of the Universe (cosmology). In other cases as, e.g., spherically symmetric systems, fully asymmetric structures, and so on, the energy-momentum tensor of the field A must be calculated from the formula (6) of Sec. II. We have verified that, in the static spherically symmetric case where, in adapted coordinates (t, r, θ, ϕ), the field has the components $(A_0(r), A_1(r), 0, 0)$, the energy-momentum tensor does not reduce to the form $-\rho_{_A} g_{\mu\nu}$. Our cosmological constant appears in the homogeneous isotropic case; namely, in cosmology. Also in this sense, we are concerned with a new type of cosmological constant.

Perturbations of the field $(A_0, 0, 0, 0)$ are being studied. The vector part of these perturbations could help to explain the isotropy violations —at large angular scales— detected in the WMAP maps of CMB temperatures (see Sec. I). In this way, the results of papers [11, 12] could be improved. Other nonlinear applications of the theory could lead to bounds, relations, or well-defined values of constants η and ε; we are also studying this possibility. Finally, generalizations of this theory could be studied, e.g., the field A^μ could be constrained to be timelike with the unit norm, and a mass term could be introduced in the Lagrangian (see comments in Sec. II).

Acknowledgments

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Addendum

While this paper was in production in Phys. Rev. D, we were advised by A. L. Maroto and J. Beltrán Jiménez, that similar conclusions were previously obtained by themselves in arXiv: 0811.0566v1 [astro-ph]. Since the first version of our paper was submitted to Physical Review on Nov 30 2008 (26 days after the paper 0811.0566v1 was included in the arXiv), the publication in PRD has been cancelled. In 0811.0566v1, the cosmological constant was interpreted in the framework of a modified theory of the electromagnetic field (Einstein-Maxwell generalization), whereas our paper was initially based on an unconstrained vector-tensor theory which was not interpreted as a theory of the electromagnetic field. The reader can verify that both theories seem to be different; however, we have recently verified –after Beltrán&Maroto complaints– that they are based on equivalent Lagrangians whose difference is a total divergence. Indeed, both papers are based on the general vector-tensor theory proposed by C. M. Will several decades ago. We would have never tried any publication based on an explicit modification of the Einstein-Maxwell equations.