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Cosmology with variable parameters and effective equation of state for dark energy

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Abstract
A cosmological constant, Λ, is the most natural candidate to explain the origin of the dark energy (DE) component in the universe. However, due to some experimental evidence that the equation of state (EOS) of the DE could be evolving with time/redshift (including the possibility that it might behave phantom-like near our time) has led theorists to emphasize that there might be a dynamical field (or some suitable combination of them) that could explain the behaviour of the DE. While this is of course one possibility, here we show that there is no imperative need to invoke such dynamical fields and that a variable cosmological constant (including perhaps a variable Newton's constant too) may account, in a natural way, for all these features.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

The phenomenon of the accelerated expansion of the universe is presently one of the central issues of both observational and theoretical cosmologies. A number of diverse cosmological observations [1, 2] have by now established the accelerated nature of the present expansion of the universe and even provided additional information on the deceleration/acceleration transition and the redshift dependence of the expansion of the universe. From the theoretical side, the sole fact that the universe is presently accelerating, and may continue to do so, has triggered many studies. Some particularly interesting possibilities include braneworld models of the late-time cosmic acceleration [3]. The real theoretical challenge, however, lies

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in understanding the dynamics leading to the accelerated expansion of the universe. Despite the fact that many promising models have been proposed, the fundamental nature of the accelerating mechanism remains presently unknown. The attempts towards shedding some light on the cause of the acceleration of the universe employ a broad range of concepts in many theoretical frameworks. The most widely used and the conceptually simplest option assumes the existence of *dark energy* (DE), the cosmic component with negative pressure. Dark energy is a very useful concept since it encodes all our ignorance on the acceleration of the universe in a single cosmic component. Furthermore, DE can also be used as an effective description of other mechanisms of the acceleration of the universe [4]. An obvious candidate for the role of DE is the cosmological constant (CC) [5]. The cosmological model with the cold dark matter and the CC as the DE component, a so-called ΛCDM cosmology, fits the data well. Theoretically, the CC as a DE candidate faces a grave problem of many orders of magnitude difference of its theoretically predicted and observed values. This huge discrepancy clearly calls for a more profound treatment of the CC problem. The inconsistencies related to the CC problem have led to the development of many dynamical DE models. The tacit assumption of these models is that the CC does not contribute to DE or that it vanishes, which merely circumvents the CC problem. The dynamical DE models, however, incorporate the advantage that they approach the modelling of the mysterious dark energy component in a more general way, allowing its properties to vary with the expansion. The dynamical DE models, among others, comprise *quintessence* [6], *phantom energy* [7], *Chaplygin gas* [8] and others. These models of DE are very often realized in terms of dynamical scalar field(s) which were introduced long ago in cosmology on more or less phenomenological grounds [9, 10]. In the quintessence approach these fields and their parameters/scales are not related to the known particle physics fields and their parameters/scales and as a consequence a clear connection to the fundamental physics is lacking. In this paper we generalize the CC concept allowing the variability of the Λ term and possibly the gravitational coupling G with the cosmic time, both assumptions are compatible with the cosmological principle. The support for such a generalization comes from the quantum field theory on the curved spacetime [11, 12] and/or quantum gravity approaches [13]. Here, however, we do not derive the variability of the aforementioned parameters from these models, but discuss the general implications of the variability of Λ and possibly G valid in any specific model of the mentioned type. Let us emphasize that this approach embodies many virtues. The problem of the CC is dealt with instead of circumventing it. The variability of Λ may shed some light on the observed value of the CC. The variable CC is indeed a type of dynamical DE, and will be handled here in the language of the effective dark energy picture.

2. Dark energy picture versus the variable cosmological constant picture

Before presenting the general procedure of obtaining the effective dark energy density corresponding to the variable CC model, we briefly discuss the frameworks of two approaches which we call *the DE picture* and *the variable CC picture*. The dark energy picture assumes the existence of two separately conserved cosmological components, the matter component and the DE component. In the Einstein equation

$$R_{\mu\nu} - \tfrac{1}{2}g_{\mu\nu}R = 8\pi G\tilde{T}_{\mu\nu}, \tag{1}$$

where the total energy–momentum tensor is $\tilde{T}_{\mu\nu} = T^{s}_{\mu\nu} + T^{D}_{\mu\nu}$. The standard energy–momentum tensors of matter $T^{s}_{\mu\nu}$ and the one for the dark energy $T^{D}_{\mu\nu}$ are conserved separately. In the framework of FRW metric, the conservation of the energy–momentum tensor for matter radiation, $\nabla^\mu T^s_{\mu\nu} = 0$, leads to the standard conservation law

$$\frac{\mathrm{d}\rho_s}{\mathrm{d}t} + \alpha H_D \rho_s = 0. \tag{2}$$

Here $\alpha = 3(1+\omega_s)$ where $\omega_s = 0$ and $1/3$ for nonrelativistic matter and radiation, respectively. The assumption that $\nabla^\mu T^D_{\mu\nu} = 0$ results in the additional conservation law for the DE:

$$\frac{\mathrm{d}\rho_D}{\mathrm{d}t} + 3(1+\omega_e) H_D \rho_D = 0. \tag{3}$$

Generally the parameter ω_e is redshift dependent, $\omega_e = \omega_e(z)$. The Hubble parameter is defined by the Friedmann equation

$$H_D^2 = \frac{8\pi G_0}{3}(\rho_s + \rho_D), \tag{4}$$

where a subscript D has been appended to H to differ expression (4) from its counterpart in the variable CC picture. The solution of the conservation laws (2) and (3) results in the following scaling laws for the components of the model:

$$\rho_s(z) = \rho_s(0)(1+z)^\alpha \tag{5}$$

and

$$\rho_D(z) = \rho_D(0)\zeta(z), \qquad \zeta(z) \equiv \exp\left\{3\int_0^z \mathrm{d}z' \frac{1+\omega_e(z')}{1+z'}\right\}.$$

Using expressions (5) and (6), the Friedmann equation acquires the form

$$H_D^2(z) = H_0^2[\tilde{\Omega}_M^0(1+z)^\alpha + \tilde{\Omega}_D^0\zeta(z)]. \tag{7}$$

The variable cosmological constant picture describes the models studied in this paper. The model incorporates the matter component, the variable CC component and, possibly although not necessarily, the variable gravitational coupling G. The variable CC model represents the modification of Einstein equation of general relativity which maintains its geometrical interpretation. The dynamical equation for gravity is given by

$$R_{\mu\nu} - \tfrac{1}{2}g_{\mu\nu}R = 8\pi G(T_{\mu\nu} + g_{\mu\nu}\rho_\Lambda), \tag{8}$$

where $T_{\mu\nu}$ stands for the energy–momentum tensor of matter. This equation demonstrates that the full covariance is maintained even if ρ_Λ and G acquire spacetime variability. In the framework of FRW metric, CC and G depend on cosmic time only, in accordance with the cosmic principle. The Friedmann equation is straightforwardly obtained from (8) and reads

$$H_\Lambda^2 = \frac{8\pi G}{3}(\rho + \rho_\Lambda). \tag{9}$$

The general Bianchi identity of the Einstein tensor leads to the covariant conservation law

$$\nabla^\mu[G(T_{\mu\nu} + g_{\mu\nu}\rho_\Lambda)] = 0, \tag{10}$$

which for the FRW metric acquires the form

$$\frac{\mathrm{d}}{\mathrm{d}t}[G(\rho + \rho_\Lambda)] + 3GH_\Lambda(\rho + p) = 0. \tag{11}$$

This 'mixed' conservation law connects the variation of ρ_Λ, G and ρ, where the scaling of the matter density ρ may be noncanonical. In this paper, we consider a very broad class of models, just assuming the variability of the aforementioned quantities, without specifying the fundamental origin of such a variation. A number of variable CC models of various kinds [14], and the renormalization group (RG) models of running ρ_Λ and G [11–13] provide the basis for the variability of these cosmological parameters. For example, the RG models [11, 12] do not determine the time dependence of ρ_Λ and G directly, but indirectly specifying them in terms of other cosmic dynamic quantities (matter density ρ, Hubble parameter H, etc):

$$\rho_\Lambda(z) = \rho_\Lambda(\rho(z), H(z), \ldots), \qquad G(z) = G(\rho(z), H(z), \ldots). \tag{12}$$

These functions usually have a monotonic dependence when expressed as functions of cosmic time or redshift. The relations (12), with the general conservation law (11), lead to the complete solution of the variable CC cosmological model. Using these solutions, the expression for the Hubble parameter becomes

$$H_\Lambda^2(z) = H_0^2[\Omega_M^0 f_M(z; r)(1+z)^\alpha + \Omega_\Lambda^0 f_\Lambda(z; r)]. \tag{13}$$

Here f_M and f_Λ are known functions of redshift which also depend on parameters $r = r_1, r_2, \ldots$ originating from the fundamental dynamics. They generally have a non-trivial dependence on z and only in the case of ΛCDM cosmology they satisfy $f_M = f_\Lambda = 1$. Furthermore, they also fulfil the conditions $f_M(0, r) = 1$ and $f_\Lambda(0, r) = 1$ in accordance with the cosmic sum rule $\Omega_M^0 + \Omega_\Lambda^0 = 1$. Note that in general the two sets of cosmological parameters in the two pictures (13) and (7) will be different, e.g. $\Delta\Omega_M \equiv \Omega_M^0 - \tilde{\Omega}_M^0 \neq 0$, because they correspond to two different fits of the same data.

3. Matching of pictures and effective dark energy equation of state

The two pictures presented in the preceding section may be considered as two separate, general DE models. In the remainder of the paper we, however, assume that they are the equivalent descriptions of the same cosmological evolution. More precisely, we study the effective DE dynamics associated with the variable CC model through the procedure named the matching of pictures. The matching of pictures requires that the expansion history of the universe is the same in both pictures, i.e. that their Hubble functions are equal, $H_D = H_\Lambda$. In this way, for a known dynamics of the variable CC model, an effective DE can be constructed. A number of general results for the behaviour of the effective DE density can be obtained with interesting implications to the observational data. The matching procedure of the two pictures $H_\Lambda^2 = H_D^2$, gives the equality connecting the dynamical cosmological quantities in both pictures, $G(\rho+\rho_\Lambda) = G_0(\rho_s+\rho_D)$. Using $H\,\mathrm{d}t = -\mathrm{d}z/(1+z)$ and the matching relation, the general Bianchi identity (11) can be written in the form

$$(1+z)\,\mathrm{d}(\rho_s+\rho_D) = \alpha(\rho_s+\rho_D-\xi_\Lambda)\,\mathrm{d}z, \tag{14}$$

where we have introduced

$$\xi_\Lambda(z) = \frac{G(z)}{G_0}\rho_\Lambda(z). \tag{15}$$

Using the scaling law (2) for ρ_s, we arrive at the compact form for the redshift evolution of the effective DE density

$$\frac{\mathrm{d}\rho_D(z)}{\mathrm{d}z} = \alpha\frac{\rho_D(z)-\xi_\Lambda(z)}{1+z}. \tag{16}$$

The integration of (16) readily yields a closed form expression for the effective DE density

$$\rho_D(z) = (1+z)^\alpha\left[\rho_D(0) - \alpha\int_0^z \frac{\mathrm{d}z'\xi_\Lambda(z')}{(1+z')^{(\alpha+1)}}\right]. \tag{17}$$

Expanding $\xi_\Lambda(z)$ around $z = -1$ one can see that $\rho_D(z) \to \xi_\Lambda(z)$ at sufficiently late time (i.e. when $z \to -1$). The expression for ω_e becomes very simple and informative using the effective DE density

$$\omega_e(z) = -1 + \frac{\alpha}{3}\left(1 - \frac{\xi_\Lambda(z)}{\rho_D(z)}\right) \equiv -1 + \epsilon(z), \tag{18}$$

where ρ_D is given by (17). From this expression it is clear that ω_e crosses the $\omega_e = -1$ line when the ξ_Λ equals ρ_D. This observation reinforces the role of the effective DE density ρ_D in the study of the CC boundary crossing in the dark energy picture[5].

4. Effective quintessence and phantom behaviour of a general variable Λ/G model

The solution of (16) can be reformulated in the following way:

$$\rho_D(z) = \xi_\Lambda(z) - (1+z)^\alpha \int_{z^*}^{z} \frac{\mathrm{d}z'}{(1+z')^\alpha} \frac{\mathrm{d}\xi_\Lambda(z')}{\mathrm{d}z'}. \tag{19}$$

Here z^* is the redshift value at which $\xi_\Lambda(z^*) = \rho_D(z^*)$. Quite remarkably, one can show that a value z^* *always* exists near present time, in the recent past, immediate future or just at $z^* = 0$. The proof of this claim is obtained by a straightforward calculation starting from the matching condition and the conditions that the general Bianchi identity (11) imposes on functions f_Λ and f_M in (13) and it stems from the relation

$$\frac{\mathrm{d}\zeta(z)}{\mathrm{d}z} = \frac{\alpha(1+z)^{\alpha-1}}{1-\tilde{\Omega}_M^0}\left(\Omega_M^0 f_M(z;r) - \tilde{\Omega}_M^0\right). \tag{20}$$

Since f_M is a continuous function of z, at the present epoch it satisfies the condition $f_M(0,r) = 1$ and the parameter difference $\Delta\Omega_M = \Omega_M^0 - \tilde{\Omega}_M^0$ is not large; from (20) it is clear that z^* is close to 0. The advantage of the formulation (19) becomes evident when one calculates the slope of the ρ_D function:

$$\frac{\mathrm{d}\rho_D(z)}{\mathrm{d}z} = -\alpha(1+z)^{\alpha-1} \int_{z^*}^{z} \frac{\mathrm{d}z'}{(1+z')^\alpha} \frac{\mathrm{d}\xi_\Lambda(z')}{\mathrm{d}z'}. \tag{21}$$

This compact expression reveals some counterintuitive and general aspects of the effective DE density evolution for variable CC models in which $\xi_\Lambda(z)$ is a monotonous function of z. Intuitively one would expect that for $\xi_\Lambda(z)$ growing/decreasing with z (decreasing/growing with expansion) ρ_D should be quintessence-like/phantom-like. Expression (21) reveals that this is not the case. Namely, for $\xi_\Lambda(z)$ growing with z, ρ_D decreases with z for $z > z^*$, i.e. in this redshift interval has the phantom-like characteristics. Only for $z < z^*$, ρ_D behaves as quintessence. Analogously, for $\xi_\Lambda(z)$ decreasing with z, ρ_D behaves like quintessence for $z > z^*$, whereas only for $z < z^*$ it becomes phantom-like. (For a concrete framework, see section 5 and figure 1.) These results illustrate that in variable CC models, the behaviour of effective DE density is generally not determined by the CC only, but by the joint behaviour of all quantities entering the general Bianchi identity (11). Especially interesting results are obtained when in the variable CC models the matter component ρ is separately conserved. In this case we have $\mathrm{d}\xi_\Lambda/\mathrm{d}t = -(\rho/G_0)\,\mathrm{d}G/\mathrm{d}t$, which results in the following expression for the slope of ρ_D:

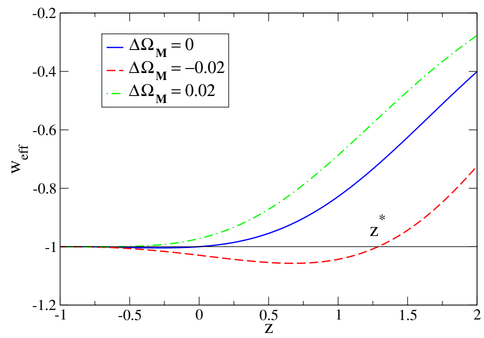
$$\frac{\mathrm{d}\rho_D}{\mathrm{d}z} = \alpha(1+z)^{\alpha-1}\frac{\rho(0)}{G_0}[G(z) - G(z^*)]. \tag{22}$$

Thus, in this case the properties of ρ_D depend only on the scaling of G with redshift, e.g. if G is asymptotically free and $z^* > z$, then ρ_D behaves effectively as quintessence.

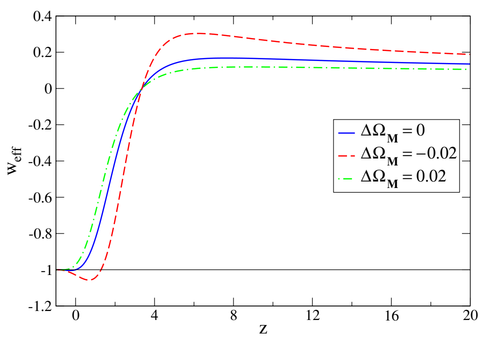
5. Effective dark energy picture of the RG model

As an illustration of the presented procedure of obtaining the effective dark energy properties, in this section we present the analysis [18] of the renormalization group

[5] For other recent theoretical approaches to the $\omega_e = -1$ boundary crossing, see e.g. [17].



(*a*)



(*b*)

Figure 1. (*a*) Numerical analysis of $\omega_{\rm eff} \equiv \omega_e$, equation (23), as a function of the redshift for fixed $\nu = -\nu_0 < 0$, and for various values of $\Delta\Omega$. The universe is assumed to be spatially flat ($\Omega_K^0 = 0$) with the standard parameter choice $\Omega_M^0 = 0.3$, $\Omega_\Lambda^0 = 0.7$; (*b*) extended z range of the plot (*a*). We see that for $\Delta\Omega < 0$ there exists a transition point z^* near our recent past: namely, the one corresponding to the crossing of the CC barrier $w = -1$ by the lowest curve in the figures.

model of [15] characterized by G = const and the $\rho_\Lambda = C_1 + C_2 H^2$ scaling. Here $C_1 = \rho_{\Lambda,0} - \left(3\nu H_0^2\right)/(8\pi G)$ and $C_2 = (3\nu)/(8\pi G)$, where ν is the single free parameter of the model—a typical value is $|\nu| = \nu_0 \equiv 1/12\pi$ [18]. This model is fully analytically tractable and simple expressions for ω_e can be obtained. In this particular case it is clear that (15) reads $\xi_\Lambda(z) = \rho_\Lambda(z)$. Therefore, for the flat universe case the effective parameter of EOS obtained from (17) and (18) is

$$\omega_e(z)|_{\Delta\Omega\neq 0} = -1 + (1-\nu)\frac{\Omega_M^0(1+z)^{3(1-\nu)} - \tilde{\Omega}_M^0(1+z)^3}{\Omega_M^0[(1+z)^{3(1-\nu)} - 1] - (1-\nu)\left[\tilde{\Omega}_M^0(1+z)^3 - 1\right]}. \tag{23}$$

For $|\nu| \ll 1$ we may expand the previous result in first order in ν. Assuming $\Delta\Omega = 0$ we find

$$\omega_e(z) \simeq -1 - 3\nu\frac{\Omega_M^0}{\Omega_\Lambda^0}(1+z)^3\ln(1+z). \tag{24}$$

This result reflects the essential qualitative features of the general analysis presented in the previous sections. For $\nu > 0$, equation (24) clearly shows that we can get an (effective) phantom-like behaviour ($\omega_e < -1$) and for $\nu < 0$ we have (effective) quintessence behaviour. We see that this variable CC model can give rise to two types of very different behaviours by just changing the sign of a single parameter. However, one can play with more parameters if desired. Indeed, as we have seen the cosmological parameters in the two pictures (DE versus CC picture) will generally be different ($\Delta\Omega \neq 0$). Figure 1 shows in a patent manner that in this case, even for $\nu < 0$, the variable CC model may exhibit phantom behaviour due to the existence of a transition point z^* in our recent past.

6. Conclusions

We have shown that a model with variable Λ and/or G generally leads to a non-trivial effective EOS, thus mimicking a dynamical DE model which can effectively appear as quintessence and even as phantom energy. The eventual determination of an empirical EOS for the DE in the next generation of precision cosmology experiments should keep in mind this possibility. Moreover, we have proven that there *always* exists a transition point z^* near $z = 0$, where $\omega_e(z^*) = -1$. If this point lies in our recent past (as illustrated in figure 1(*a*)) there could have been a recent transition into an (effective) phantom regime $\omega_e(z) \leqslant -1$, as suggested by several analyses of the data [19]. We conclude that variable (ρ_Λ, G) models may account for the observed evolution of the DE, without the need for invoking any combination of fundamental quintessence and phantom fields.

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