

Local constraints on the oscillating G model

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We analyze observational constraints on the effective Brans-Dicke parameter and on the temporal variation of the effective gravitational constant within the context of the oscillating G model, a cosmological model based on a massive scalar field nonminimally coupled to gravity. We show that these local constraints cannot be satisfied simultaneously once the values of the free parameters entering the model become fixed by the global attributes of our Universe. In particular, we show that the lower observational bound for the effective Brans-Dicke parameter and the upper bound of the variation of the effective gravitational constant lead to a specific value of the oscillation amplitude which lies well below the value required to explain the periodicity of $128h^{-1}$ Mpc in the galaxy distribution observed in the pencil beam surveys.

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I. INTRODUCTION

The success of the standard cosmological model in describing the evolution of our Universe, beginning with the era of nucleosynthesis until the present state, has been confronted with serious difficulties resulting from the analysis of cosmological data. At large cosmological scales we find two main problems which are not dealt with within the framework of the standard (old) cosmological model. The first one concerns the cosmological dark matter problem, according to which the luminous matter (baryonic matter and radiation) content of the Universe represents only a small fraction of the total matter content. In fact, the inflationary models predicted that the total energy density $\Omega = 1$, with Ω given in terms of the critical energy density [1]. This prediction was recently given further support by observational data resulting from the recent cosmic microwave background (CMB) experiments such as Boomerang and Maxima and the high redshift supernovae (SNIa) measurements [2], leading to the conclusion that the average energy-density of the Universe is indeed near the critical value. Obviously, these observations have increased the importance of the dark matter problem for the understanding of our Universe.

The second problem is related to observations that indicate a periodicity of $128h^{-1}$ Mpc (where h is the Hubble parameter in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$) in the galaxy number distribution, observed in deep pencil beams [3,4] in the north and south poles of our galaxy. This shocking discovery would, in its simplest interpretation, indicate that galaxies in the Universe are situated on the surface of concentric spheres, with the center situated in our own galaxy. This is in complete contradiction with the basis of modern cosmology: the cosmological principle of homogeneity and isotropy of the Universe. It was argued [4], and it seems to be the prevailing view among researchers in the field, that this period-

icity could be the result of the appearance of an intrinsic length scale in the distribution of matter. However, we have shown [5] that this explanation is not really satisfactory, as there are scenarios of this type that result in a negligible probability for such observation to be obtained in a particular direction.

In a series of works [6–9] we investigated an alternative model based on a massive scalar field which is nonminimally coupled to gravity. The oscillation of the scalar field in cosmic time results in a time-dependent effective gravitational constant. We have shown that this model leads to predictions which are in good agreement with most of the observational data. In fact, although this model was originally proposed [10] to explain the observed periodicity in the galaxy number distribution, we have shown that it was possible to adjudicate most of the energy density of the Universe to the oscillating massive scalar field which, therefore, could be regarded as a candidate for the nonbaryonic nature of the cosmological dark energy. That is, this model is able to explain simultaneously both the problem of the cosmological dark energy and the problem of the periodicity in the galaxy number distribution. We have checked that the model satisfies some of the cosmological constraints. More precisely, we have seen that the model correctly reproduces the primordial nucleosynthesis of ${}^4\text{He}$, and is consistent with the present value of the energy density of baryonic matter and the age of the Universe. In this work, we will analyze the additional constraints following from local observations, namely, the Viking experiments [11], which impose bounds on the rate of change in time of the effective gravitational constant and on the effective Brans-Dicke parameter.

In a previous work [12] we have shown that all but one of the free parameters entering the model are fixed by the cosmological analysis, and that with these values it was not possible to satisfy the Brans-Dicke bound. In this work, we analyze the possibility of overcoming this problem by relaxing the single condition freely imposed in our previous cosmological studies. We will show that even with this relaxation it is not possible to satisfy the local constraints and the periodicity observations simultaneously. This result indicates that either the behavior of the scalar field in the presence of

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local inhomogeneities is different from its behavior at large scales [12] or that a modified model would be necessary if we want to explain in a unified way the apparent galactic periodicity and the cosmological dark energy.

II. CONSTRAINTS ON THE OSCILLATING G MODEL

The dynamics of oscillating G model is described by the Lagrangian

$$\mathcal{L} = \left(\frac{1}{16\pi G_0} + \xi \phi^2 \right) \sqrt{-g} R - \sqrt{-g} \left[\frac{1}{2} (\nabla \phi)^2 + V(\phi) \right], \quad (1)$$

where G_0 is Newton's gravitational constant, ξ stands for the nonminimally coupling constant, R is the scalar curvature, ϕ is the scalar field, and $V(\phi)$ is a scalar potential which in its simplest form is taken as the harmonic potential $V = m^2 \phi^2$, with m the mass of the scalar field. If we consider a time-dependent scalar field, the nonminimal coupling results in a time-dependent effective gravitational constant $G_{\text{eff}} = G_0 (1 + 16\pi G_0 \xi \phi^2)^{-1}$. The central feature of the oscillating G model is that oscillations in the expectation value of ϕ induce oscillations in G_{eff} , and this leads to oscillations in the Hubble parameter H which manifest themselves in the redshift measurements of distant points of the Universe. In turn, the redshift oscillations give rise to an apparent variation in the density of galaxies. Consequently, a temporal oscillation of the redshift can be mistakenly interpreted as a real spatial periodicity in the galaxy number distribution. This was used in previous works [6–9] to explain the observed periodicity of $128h^{-1}$ Mpc in the distribution of galaxies in our Universe. To this end, we analyzed the Friedman-Robertson-Walker cosmology with a combination of two noninteracting perfect fluids (radiation and baryonic matter). From the field equations we obtain the following expression for the total effective energy density of the system (see Refs. [6,8]):

$$\Omega_{\text{tot}} = \frac{1}{1 + 16\pi \xi \phi_0^2} \left[\Omega_{\text{mat}} + \frac{4\pi}{3} \dot{\phi}_0^2 + \frac{4\pi}{3} \tilde{\omega}^2 \phi_0^2 - 32\pi \xi \phi_0 \dot{\phi}_0 \right], \quad (2)$$

where

$$\dot{\phi}_0 = \left. \frac{d\phi}{dt} \right|_{\text{today}}, \quad \tilde{t} = tH_0, \quad \tilde{\omega} = \frac{\omega}{H_0}, \quad \tilde{m}^2 = \frac{4\pi}{3} \tilde{\omega}^2. \quad (3)$$

In the above equation, the subscript 0 stands for the value of the corresponding quantity at present time $t = t_0$. The frequency of oscillation $\omega = m\sqrt{3/4\pi}$ is determined by the period of $128h^{-1}$ Mpc observed in the pencil beam surveys and turns out to be $\omega \approx 147H_0$. Here $\Omega_{\text{matt}} = \Omega_{\text{bar}} + \Omega_{\text{rad}}$. Note that in Eq. (2) and for the present analysis we can neglect the contribution of the photon energy density Ω_{rad} , because the observations of the cosmic microwave background radiation of 2.725 K implies that $\Omega_{\text{rad}} \approx 10^{-3} \Omega_{\text{bar}}$ [13]. Furthermore, the value of Ω_{bar} must lie within the range $[0.01, 0.02]h^{-2}$ determined by the abundance of light elements other than ${}^4\text{He}$ [14]. Finally, for the total energy den-

sity we take the value $\Omega_{\text{tot}} = 1$ in accordance with the standard inflationary model and with the recent CMB and SNIa observations [2]. Consequently, Eq. (2) can be interpreted as a constraint relating the initial cosmological values of the scalar field, ϕ_0 and $\dot{\phi}_0$, and the coupling parameter ξ . Another, in some sense, more realistic approach would be to identify Ω_{matt} with the total amount of clumped matter in our Universe which would include besides the baryonic component also the so called cold dark matter, leading us to take $\Omega_{\text{matt}} \sim 0.3$. However, we will see that even this drastic change of view does not alter our conclusions in a significant way.

A further constraint is imposed by the observed redshift-galaxy-count amplitude $\mathcal{A}_0 \geq O(0.5)$, which for the oscillating G model can be approximated by the expression [15]

$$\mathcal{A}_0 = \frac{16\pi \xi}{\tilde{\omega}} (\tilde{\omega}^2 \phi_0^2 + \dot{\phi}_0^2). \quad (4)$$

Here we are considering the additional term $\dot{\phi}_0^2$ which was set to zero in previous analysis because we want to remove all the arbitrarily imposed conditions on the model in order to examine whether all the constraints can be solved simultaneously. Since the values of \mathcal{A}_0 and $\tilde{\omega}$ are fixed by the pencil beam observations, Eq. (4) represents a constraint between the values of ϕ_0 , $\dot{\phi}_0$, and ξ . We call Eqs. (2) and (4) global constraints of the oscillating G model because the values of \mathcal{A}_0 and $\tilde{\omega}$ are fixed by the large scale observations of the galactic periodicity, and the values of Ω_{tot} and Ω_{matt} are the result of global cosmological observations.

On the other hand, the Solar System local observations impose an upper bound on the variation of the gravitational constant $|\dot{G}/(GH)|_{\text{today}} \leq 0.3h^{-1}$ [15]. For the oscillating G model, this yields

$$\beta = \left. \frac{\dot{G}_{\text{eff}}}{G_{\text{eff}} H} \right|_{\text{today}} = - \frac{32\pi \xi \phi_0 \dot{\phi}_0}{1 + 16\pi \xi \phi_0^2} \quad \text{with } |\beta| \leq 0.3. \quad (5)$$

It is well known that scalar-tensor models of the kind defined by the Lagrangian [Eq. (1)] can be transformed by means of a conformal transformation into an effective Brans-Dicke theory. Then such models can be characterized by an effective Brans-Dicke parameter $\omega_{\text{BD}}^{\text{eff}}$ which must satisfy the lower bound imposed by the Viking experiments [11], $\omega_{\text{BD}}^{\text{eff}} > 3000$. In the case of the oscillating G model, we obtain

$$\omega_{\text{BD}}^{\text{eff}} = \frac{1 + 16\pi \xi \phi_0^2}{128\pi \xi^2 \phi_0^2}, \quad (6)$$

a constraint that relates ϕ_0 with ξ .

Now we proceed to an analysis of the global constraints [Eqs. (2) and (4)] and the local constraints [Eqs. (5) and (6)]. In our previous cosmological studies, we were able to satisfy simultaneously the total energy constraint [Eq. (2)] as well as the nucleosynthesis and age constraints, together with the constraints for the amplitude [Eq. (4)] and the variation of

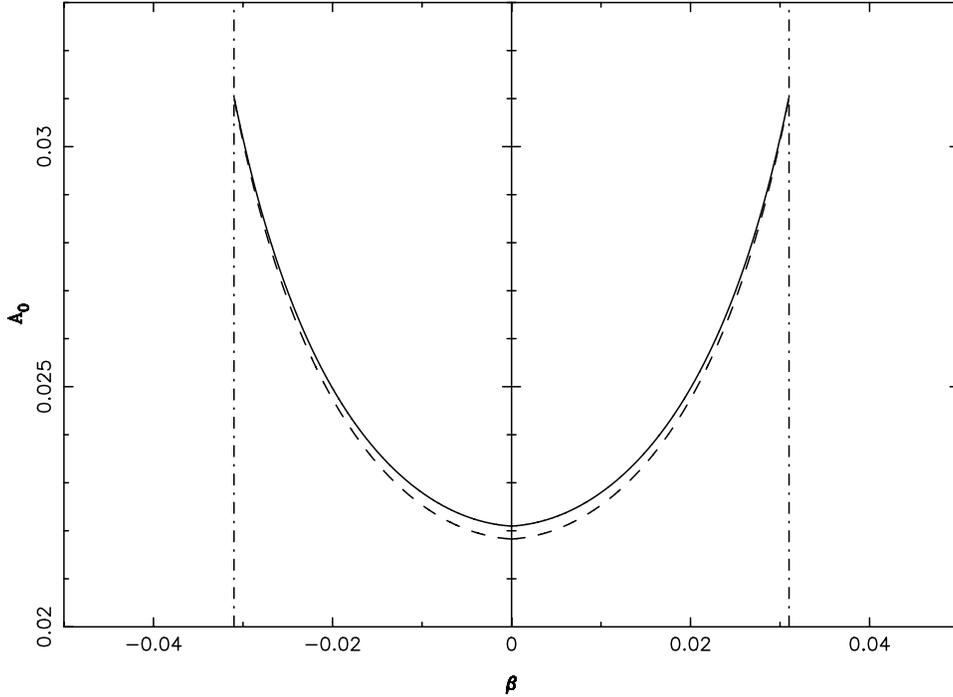


FIG. 1. The redshift-count-oscillation amplitude \mathcal{A}_0 as a function of the parameter β satisfying constraint (7) for $\omega_{\text{BD}}=3000$. The solid line corresponds to a value of $\Omega_{\text{mat}}=0.02366$, and the dashed line to $\Omega_{\text{mat}}=0.04733$. The dash-dotted lines show the limits for which the constraint (7) is valid. Here we took $H_0=65 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

the effective gravitational constant [Eq. (5)] by setting $\tilde{\phi}_0=0$. In fact, in this case constraint (5) is automatically satisfied ($\beta=0$), whereas the constraints (2) and (4), together with the “plateau hypothesis” [8] that ensures a successful nucleosynthesis, fix the values of the remaining parameters ϕ_0 ($\sim 10^{-3}$) and ξ (~ 6). The evolution of the model with these conditions result in a value for the age of the Universe compatible with the standard bounds [16].

However, as we showed in Ref. [12], with these values the oscillating G model is unable to satisfy the Brans-Dicke limit [Eq. (6)] with $\omega_{\text{BD}}^{\text{eff}}>3000$ (or even the less severe bound $\omega_{\text{BD}}^{\text{eff}}>500$). The simplest possible way to overcome this problem is to relax the condition $\tilde{\phi}_0=0$ within the range allowed by constraints (4) and (5). To this end, we replace the values of ϕ_0 , $\tilde{\phi}_0$, and ξ following from constraints (4), (5), and (6) into the total energy constraint [Eq. (2)]. Then we obtain

$$f(\omega_{\text{BD}}^{\text{eff}}, \beta, \mathcal{A}_0) = 1 - \Omega_{\text{mat}} - \frac{2b\tilde{\omega}\omega_{\text{BD}}^{\text{eff}}\mathcal{A}_0}{3(a+b)} + \frac{b + 2\sqrt{a\tilde{\omega}\mathcal{A}_0 - b\tilde{\omega}^2}}{a} = 0, \quad (7)$$

with

$$a = \beta^2 + 4\tilde{\omega}^2, \quad (8)$$

$$b = -\beta^2 + 2\tilde{\omega}\mathcal{A}_0 + 2\sqrt{\tilde{\omega}^2(\mathcal{A}_0^2 - \beta^2) - \beta^2\tilde{\omega}\mathcal{A}_0},$$

a constraint that, for a specific value of Ω_{mat} , determines the amplitude in terms of the effective Brans-Dicke parameter and the parameter β (recall that the frequency $\tilde{\omega}$ has been fixed by the period of oscillation). Note that the initial values ϕ_0 and $\tilde{\phi}_0$ do not appear at all in Eq. (7). In order to investigate constraint (7) in a systematic way we have to solve the algebraic equation (7) as $\mathcal{A}_0 = \mathcal{A}_0(\beta)$. Actually this is equivalent to solving the differential equation $df(\beta, \mathcal{A}_0(\beta))/d\beta = 0$ [i.e., the resulting differential equation $d\mathcal{A}_0/d\beta = F(\mathcal{A}_0, \beta)$] subject to the boundary values $(\beta^i, \mathcal{A}_0^i)$, such that $f(\beta^i, \mathcal{A}_0^i) = 0$, for a fixed $\omega_{\text{BD}}^{\text{eff}}$ and Ω_{mat} . For instance, for $\tilde{\phi}_0=0$, and $\omega_{\text{BD}}^{\text{eff}}=3000$, $\Omega_{\text{mat}}=0.0236$ the pair $(\beta^i=0, \mathcal{A}_0^i \approx 0.022)$ satisfies constraint (7) as well as the remaining conditions (except of course the order of magnitude in the bound on \mathcal{A}_0). The result of this calculation is plotted in Fig. 1 for two different values of Ω_{mat} within the range allowed by observations. We see that the range of values (β, \mathcal{A}_0) that satisfy $f(\beta, \mathcal{A}_0) = 0$ is extremely narrow, and that all of the values for the amplitude within this range are situated well below the lower bound $\mathcal{A}_0 \geq O(0.5)$ imposed by the redshift-galaxy-count observations. The conclusion is that the Brans-Dicke local constraint is not compatible with the observed value for the oscillation amplitude. Further numerical analysis of constraint (7) shows that an increase of the matter density Ω_{mat} or of the effective Brans-Dicke parameter leads to even lower values for the amplitude.

We conclude that the relaxation of the original condition $\tilde{\phi}_0=0$ does not allow the oscillating G model to satisfy both global and local constraints simultaneously, and that we have

to look for further generalizations of this model if we want to consider it as a candidate to explain the apparent galactic periodicity simultaneously with the nature of the nonbaryonic dark matter content in the Universe. Needless to say, had the model succeeded in these tests, it would then be necessary to confront the oscillating G model to further tests in light of the recent CMB and SNIa observations.

Finally, it is worthwhile to emphasize that the generalized view on the problem of the galactic periodicity is that perhaps there is no problem at all and that such a “periodicity” is only the result of an excess of power at some characteristic length scales. While this could be the case, the simplest analysis of this matter shows that the existence of a characteristic distance in the large scale distribution is not enough to explain such observations [5], and therefore serious doubts arise when taking such a comfortable position. Clearly, the

observation of galactic periodicity or lack thereof in directions other than those corresponding to the north and south galactic poles will put an end to the controversy. On the other hand, if the existence of such periodicities in a large number of directions were to be confirmed, we would be in the uncomfortable situation of having no model to account for it, and we would need to resort to variations on the oscillating G model presented here as the only types of scenarios capable of explaining such observations within the context of the cosmological principle.

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- [1] A.H. Guth, *Phys. Rev. D* **23**, 347 (1981); A. Linde, *Phys. Lett.* **108B**, 389 (1982).
- [2] P. de Berdarnis *et al.*, *Nature (London)* **404**, 955 (2000); S. Hanany *et al.*, *Astrophys. J. Lett.* **545**, L5 (2000); A.G. Riess *et al.*, *Astron. J.* **116**, 1009 (1998); S. Perlmutter *et al.*, *Astrophys. J.* **517**, 565 (1999).
- [3] T. Broadhurst, R. Ellis, D. Koo, and A. Szalay, *Nature (London)* **343**, 726 (1990); A. Szalay, R. Ellis, D. Koo, and T. Broadhurst, in *Primordial Nucleosynthesis and Evolution of the Universe*, edited by K. Sato and J. Audouze (Kluwer, Dordrecht, 1991), p. 435.
- [4] A. Szalay, T.J. Broadhurst, N. Ellman, D.C. Koo, and R.S. Ellis, *Proc. Natl. Acad. Sci. U.S.A.* **90**, 4853 (1993).
- [5] J.A. Gonzalez, H. Quevedo, M. Salgado, and D. Sudarsky, *Astron. Astrophys.* **362**, 835 (2000).
- [6] M. Salgado, D. Sudarsky, and H. Quevedo, *Phys. Rev. D* **53**, 6771 (1996).
- [7] M. Salgado, D. Sudarsky, and H. Quevedo, *Phys. Lett. B* **408**, 69 (1997).
- [8] H. Quevedo, M. Salgado, and D. Sudarsky, *Astrophys. J.* **488**, 14 (1997).
- [9] D. Sudarsky, H. Quevedo, and M. Salgado, *Rev. Mex. Fís.* **43**, 699 (1997).
- [10] M. Morikawa, *Astrophys. J. Lett.* **362**, L37 (1990).
- [11] R.D. Reasenberg *et al.*, *Astrophys. J., Lett. Ed.* **234**, L219 (1979). Usually, the Brans-Dicke bound is taken as $\omega_{BD} > 500$. However, here we take $\omega_{BD} > 3000$, in accordance with more recent observations [C. Will (private communication)].
- [12] H. Quevedo, M. Salgado, and D. Sudarsky, *Gen. Relativ. Gravit.* **31**, 767 (1999).
- [13] Obviously we cannot neglect the photon contribution when we evolve the equations backward in time in order to recover the nucleosynthesis predictions.
- [14] C. Copi, D.N. Schram, and M.S. Turner, *Science* **267**, 192 (1995).
- [15] R.G. Crittenden, and P.J. Steinhardt, *Astrophys. J.* **395**, 360 (1992).
- [16] L.M. Krauss, *Phys. Rep.* **333-334**, 33 (2000).