New agegraphic dark energy as a rolling tachyon*

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(Received 9 April 2009; revised manuscript received 5 May 2009)

Combining the general relativity and the uncertainty relation in quantum mechanics, the energy density of quantum fluctuations of space-time can be viewed as dark energy. The so-called agegraphic dark energy model is just based on this viewpoint, in which the age of the universe is introduced as the length measure. Recently, the new agegraphic dark energy model was proposed, where the dynamical dark energy is measured by the conformal age of the universe. On the other hand, scalar-field dark energy models like tachyons are often regarded as an effective description of some underlying theory of dark energy. In this paper, we show that the new agegraphic dark energy can be described completely by a tachyon scalar-field. We thus reconstruct the potential and the dynamics of the tachyon scalar-field, according to the evolution of the new agegraphic dark energy.

Keywords: new agegraphic dark energy, tachyon, reconstruction

PACC: 9880B

Nowadays it is strongly believed that the universe is currently undergoing accelerated expansion. Astronomical observations, such as searches for type Ia supernovae (SNIa),[1] observations of large scale structure (LSS)[2] and measurements of the cosmos microware background (CMB) anisotropy,[3] have provided the main evidence for this cosmic acceleration. The most accepted idea is that this cosmic acceleration is caused by a mysterious energy component, usually dubbed 'dark energy', with negative pressure, whose energy density has been a dominant power in the universe. A distinct feature of dark energy is that it is unclustered, differing from baryons and nonbaryonic cold dark matter that have features of gravitational clustering. The combined analysis of cosmological observations indicates that the universe is spatially flat, and consists of about 70% dark energy, 30% dust matter (cold dark matter plus baryons), and negligible radiation. Though the nature of dark energy is still unknown, we can affirm that the ultimate fate of the universe is determined by the nature of dark energy. Currently the central problem is to reveal the nature of dark energy in both cosmology and theoretical physics research. To interpret or describe its properties, many candidates for dark energy have been proposed. The famous cosmological constant introduced first by Einstein in 1917 is the simplest candidate for dark energy. However, the cosmological constant scenario has to face the so-called 'fine-tuning problem' and 'coincidence problem'.[4] The cosmological constant problem is essentially an issue of quantum gravity, because it concerns the vacuum expectation value of some quantum fields. However, we do not yet have a complete theory of quantum gravity. But theorists have been making lots of efforts to try to resolve the cosmological constant problem by various means.

Another candidate for dark energy is the dynamical scalar field model whose energy density is associated with a slowly varying scalar field. The scalar field models can be viewed as an effective description of the underlying theory of dark energy. An example of scalar-field dark energy is the so-called 'quintessence',[5] a scalar field slowly evolving down its potential. Provided that the evolution of the field is slow enough, the kinetic energy density is less than the potential energy density, giving rise to the negative pressure responsible for cosmic acceleration. So far, besides quintessence, a wide variety of scalar-field dark energy models have been studied, including the K-essence,[6] phantom,[7] tachyon,[8] quintom,[9] ghost condensate,[10] etc. In addition, there are other proposals on dark energy such as interacting dark energy models,[11] brane world models,[12] Chaplygin gas models,[13] and so on. However, one should realize that these models are almost settled at the phenomenological level.

In recent years, many string theorists have been devoted to shedding light on the cosmological constant or dark energy within the string framework. The famous Kachru–Kallosh–Linde–Trivedi (KKLT)

*Project supported by the National Natural Science Foundation of China (Grant No. 10705041).
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model[14] is a typical example, which tries to construct metastable de Sitter vacua in the light of type IIB string theory. Furthermore, the string landscape idea has been proposed to shed light on the cosmological constant problem based upon anthropic principle and multiverse speculation. Besides, according to some principles of quantum gravity, we still can make some attempts to probe the properties of dark energy within the fundamental theory framework although a complete theory of quantum gravity is not available today. The holographic dark energy model[15,16] and the agegraphic dark energy model[17,18] are just appropriate examples, which originated from some considerations of the quantum theory of gravity. The holographic dark energy model is constructed in the light of the holographic principle of quantum gravity theory, and the agegraphic dark energy model takes into account the well-known Heisenberg uncertainty relation of quantum mechanics together with the gravitational effect in general relativity. In this regard, the holographic and agegraphic dark energy scenarios may possess some significant features of an underlying theory of dark energy.

As mentioned above, scalar field models can be regarded as effective models of the underlying theory. In this sense, it is interesting and meaningful to study how scalar field models can be used to describe dark energy scenarios possessing some significant features of quantum gravity theory, such as holographic and agegraphic dark energy models. In this direction, much work has been done; see, e.g., [19] In this paper, we intend to reconstruct the potential and dynamics of the tachyon scalar-field from the new agegraphic dark energy model.

Let us first briefly review the models of agegraphic dark energy. Based on quantum field theory, an ultraviolet (UV) cutoff is related to an infrared (IR) cutoff due to the limit set by formation of a black hole. This means that if ρ_Λ is the quantum zero-point energy density caused by UV cutoff, the total energy in a region of size L should not exceed the mass of a black hole of the same size. The largest IR cut-off L is chosen by saturating the inequality $L^3\rho_\Lambda \leqslant LM_{\rm p}^2$, so that we obtain the holographic dark energy density[15]

$$\rho_\Lambda = 3c^2 M_{\rm p}^2 L^{-2} \ , \tag{1}$$

where c is a numerical constant, and $M_{\rm p} \equiv 1/\sqrt{8\pi G}$ is the reduced Planck mass. Now the problem we have is how to choose the IR cutoff. If the current Hubble horizon acts as the IR cutoff, the equation of state of dark energy is the same as that of dark matter, and it cannot lead to a universe with accelerating expansion. For similar reason, the particle horizon of the universe also cannot be used. Although the event horizon of the universe acting as the IR cutoff can reach a good conclusion that the universe can undergo accelerated expansion, and the vacuum energy density in this case can fit the data well, it is surprising for us that the current dark energy density is determined by the future evolution of the universe, rather than the past of the universe.

Following the line of quantum fluctuations of spacetime, Károlyházy *et al.*[20] proposed that the distance t in Minkowski spacetime cannot be known to a better accuracy than

$$\delta t = \lambda t_{\rm p}^{2/3} t^{1/3}, \tag{2}$$

where λ is a dimensionless constant of order unity. We use the units $\hbar = c = k_{\rm B} = 1$ throughout this work. Thus $l_{\rm p} = t_{\rm p} = 1/M_{\rm p}$ with $l_{\rm p}$ and $t_{\rm p}$ being the reduced Planck length and time, respectively.

The Károlyházy relation (2) together with the time–energy uncertainty relation enables one to estimate a quantum energy density of the metric fluctuations of Minkowski spacetime.[21,22] Following Refs. [21] and [22], with respect to Eq. (2) a length scale t can be known with a maximum precision δt determining thereby a minimal detectable cell $\delta t^3 \sim t_{\rm p}^2 t$ over a spatial region t^3. Such a cell represents a minimal detectable unit of spacetime over a given length scale t. If the age of the Minkowski spacetime is t, then over a spatial region with linear size t (determining the maximal observable patch) there exists a minimal cell δt^3 whose energy due to the time–energy uncertainty relation cannot be smaller than

$$E_{\delta t^3} \sim t^{-1} \ . \tag{3}$$

Therefore, the energy density of metric fluctuations of Minkowski spacetime is given by[21,22]

$$\rho_{\rm q} \sim \frac{E_{\delta t^3}}{\delta t^3} \sim \frac{1}{t_{\rm p}^2 t^2} \sim \frac{M_{\rm p}^2}{t^2} \ . \tag{4}$$

In the original version of the agegraphic dark energy model,[16] the time scale t in Eq. (4) is chosen to be the age of the universe

$$t = \int_0^a \frac{{\rm d}a}{Ha}, \tag{5}$$

where a is the scale factor of our universe; $H \equiv \dot{a}/a$ is the Hubble parameter; a dot denotes the derivative with respect to cosmic time.

To avoid some internal inconsistencies in the original model, the so-called 'new agegraphic dark energy' (NADE) model[18] was proposed, where the time scale in Eq. (4) is chosen to be conformal time η instead of the age of the universe,

$$\eta \equiv \int_0^t \frac{\mathrm{d}t}{a} = \int_0^a \frac{\mathrm{d}a}{a^2 H}. \tag{6}$$

Consequently the energy density of NADE is

$$\rho_{\mathrm{q}} = \frac{3n^2 M_{\mathrm{p}}^2}{\eta^2}, \tag{7}$$

where the numerical factor $3n^2$ is introduced to parameterize some uncertainties, such as the species of quantum fields in the universe, the effect of curved spacetime (since the energy density is derived for Minkowski spacetime), and so on.

We consider a spatially flat Friedmann–Robertson–Walker (FRW) universe with dark energy and pressureless matter, so the corresponding Friedmann equation reads

$$H^2 = \frac{1}{3M_{\mathrm{p}}^2}\left(\rho_{\mathrm{m}} + \rho_{\mathrm{q}}\right). \tag{8}$$

For NADE, the corresponding fractional energy density is given by

$$\Omega_{\mathrm{q}} = \frac{n^2}{H^2\eta^2}. \tag{9}$$

By using Eqs. (6)–(8) and the energy conservation equation $\dot{\rho}_{\mathrm{m}} + 3H\rho_{\mathrm{m}} = 0$, we find that the equation of motion for Ω_{q} is given by

$$\frac{\mathrm{d}\Omega_{\mathrm{q}}}{\mathrm{d}a} = \frac{\Omega_{\mathrm{q}}}{a}\left(1-\Omega_{\mathrm{q}}\right)\left(3 - \frac{2}{n}\frac{\sqrt{\Omega_{\mathrm{q}}}}{a}\right). \tag{10}$$

Also, we can rewrite Eq. (10) as

$$\frac{\mathrm{d}\Omega_{\mathrm{q}}}{\mathrm{d}z} = -\Omega_{\mathrm{q}}(1-\Omega_{\mathrm{q}})\left[3(1+z)^{-1} - \frac{2}{n}\sqrt{\Omega_{\mathrm{q}}}\right], \tag{11}$$

where $z = 1/a - 1$ is the redshift of the universe.

From the energy conservation equation $\dot{\rho_{\mathrm{q}}} + 3H(\rho_{\mathrm{q}} + p_{\mathrm{q}}) = 0$, as well as Eqs. (7) and (9), it is easy to find that the equation-of-state of NADE, $w_{\mathrm{q}} \equiv p_{\mathrm{q}}/\rho_{\mathrm{q}}$, is given by

$$w_{\mathrm{q}} = -1 + \frac{2}{3n}(1+z)\sqrt{\Omega_{\mathrm{q}}}. \tag{12}$$

It is worth noting that the new agegraphic dark energy model is a single-parameter model. As mentioned in Ref. [23], if n is given, we can get $\Omega_{\mathrm{q}}(z)$ from Eq. (11) with the initial condition $\Omega_{\mathrm{q}}(z_{\mathrm{ini}}) = n^2(1+z_{\mathrm{ini}})^{-2}/4$. The initial condition can be chosen at, for example, $z_{\mathrm{ini}} = 2000$, as in Ref. [23]. After that, other physical quantities, such as $\Omega_{\mathrm{m}}(z) = 1 - \Omega_{\mathrm{q}}(z)$ and $w_{\mathrm{q}}(z)$, can be obtained. We plot the evolution curves of w_{q} in Fig. 1 with different n, choosing the redshift range $-1 < z \leq 20$. From this figure, we can see that at later times ($z \to -1$ and $\Omega_{\mathrm{q}} \to 1$), we have $w_{\mathrm{q}} \to -1$; the new agegraphic dark energy mimics a cosmological constant. When $z = 20$, we have $w_{\mathrm{q}} \to -2/3$, no matter which value of n we choose.

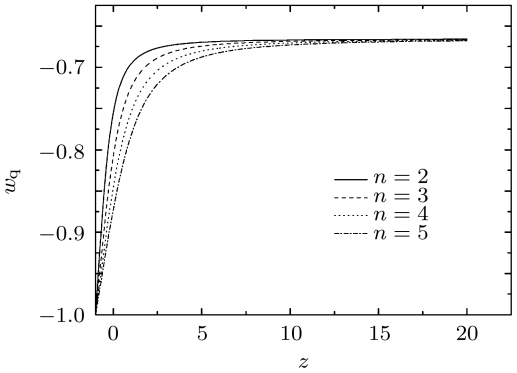


Fig. 1. The evolution of the equation of state of the new agegraphic dark energy with different n. Here we use the initial condition $\Omega_{\mathrm{q}}(z_{\mathrm{ini}}) = n^2(1+z_{\mathrm{ini}})^{-2}/4$ at $z_{\mathrm{ini}} = 2000$.

Next, we shall reconstruct the tachyon scalar-field from the new agegraphic dark energy. The rolling tachyon condensate in a class of string theories may have interesting cosmological consequences. It has been shown by Sen[8] that the decay of D-branes produces a pressureless gas with finite energy density that resembles classical dust. A rolling tachyon has an interesting equation of state whose parameter smoothly interpolates between -1 and 0.[24] Thus, a tachyon can be viewed as a suitable candidate for the inflaton at high energy.[25] Meanwhile, the tachyon can also act as a source of dark energy depending upon the form of the tachyon potential.[26] The effective Lagrangian for the tachyon on a non-BPS D3-brane is described by

$$S = -\int \mathrm{d}^4x V(\phi)\sqrt{-\det(g_{ab} + \partial_a\phi\partial_b\phi)}, \tag{13}$$

where $V(\phi)$ is the tachyon potential. The corresponding energy momentum tensor has the form

$$T_{\mu\nu} = \frac{V(\phi)\partial_\mu\phi\partial_\nu\phi}{\sqrt{1+g^{\alpha\beta}\partial_\alpha\phi\partial_\beta\phi}} - g_{\mu\nu}V(\phi)\sqrt{1+g^{\alpha\beta}\partial_\alpha\phi\partial_\beta\phi}. \tag{14}$$

In a flat FRW background the energy density and pres-

sure for the tachyon field are as follows:

$$\rho_\phi = -T_0^0 = \frac{V(\phi)}{\sqrt{1-\dot{\phi}^2}}, \tag{15}$$

$$p_\phi = T_i^i = -V(\phi)\sqrt{1-\dot{\phi}^2}. \tag{16}$$

Consequently the equation of state of the tachyon is given by

$$w_\phi = p_\phi/\rho_\phi = \dot{\phi}^2 - 1. \tag{17}$$

We see that irrespective of the steepness of the tachyon potential, the equation of state varies between 0 and -1. Clearly, the tachyonic scalar field cannot realize the equation of state crossing -1.

Imposing the feature of NADE on the tachyon scalar-field, we should identify ρ_ϕ with $\rho_{\rm q}$. In the following we do not distinguish between the subscripts 'ϕ' and 'q'. From Eq. (8), we obtain

$$H(z) = H_0\left(\frac{\Omega_{\rm m0}(1+z)^3}{1-\Omega_{\rm q}}\right)^{1/2}. \tag{18}$$

Using Eqs. (15), (16) and (18), the tachyon potential can be written as

$$\frac{V(\phi)}{\rho_{\rm c0}} = \frac{\Omega_{\rm q}\Omega_{\rm m0}(1+z)^3}{1-\Omega_{\rm q}}\sqrt{-w_{\rm q}}, \tag{19}$$

where $\rho_{\rm c0} = 3M_{\rm p}^2H_0^2$ is today's critical density of the universe. Moreover, using Eqs. (17) and (18), the derivative of the tachyon scalar-field ϕ with respect to the redshift z can be given by

$$\frac{\phi'}{H_0^{-1}} = \pm\sqrt{\frac{(1-\Omega_{\rm q})(1+w_{\rm q})}{\Omega_{\rm m0}(1+z)^5}}, \tag{20}$$

where the plus/minus sign is actually arbitrary since it can be changed by the redefinition of the field, $\phi \to -\phi$. Consequently, we can easily obtain the evolutionary form of the tachyon field

$$\phi(z) = \int_0^z \phi'\,{\rm d}z, \tag{21}$$

by fixing the field amplitude at the present epoch ($z = 0$) to be zero, $\phi(0) = 0$.

Tachyon models with different potential forms have been discussed widely in the literature. For the tachyon model constructed from the NADE, the potential, $V(\phi)$, as well as the dynamical evolution of the field, $\phi(z)$, can be determined by Eqs. (19)–(21). The analytical form of the potential $V(\phi)$ cannot be derived due to the complexity of these equations, but we can obtain the tachyon potential numerically. Using the numerical method, the tachyon potential $V(\phi)$ is plotted in Fig. 2, where $\phi(z)$ is also obtained according to Eqs. (20) and (21), and displayed in the left panel of Fig. 3. In the right panel of Fig. 3, we plot the kinetic energy density as a function of the field, namely $\dot{\phi}^2(\phi)$. Actually, Fig. 3 shows the dynamics of the tachyon scalar-field, reconstructed according to the evolution of the new agegraphic dark energy. Selected curves are plotted for the cases of $n = 2$, 3, 4 and 5. From Fig. 2, it is clear to see that the reconstructed tachyon potential is steeper in the early epoch ($z > 2.5$) and becomes very flat near today, according to the evolution of NADE. Consequently, the tachyon scalar-field ϕ rolls down the potential with the kinetic energy $\dot{\phi}^2$ gradually decreasing, as indicated in Fig. 3. The equation of state of the tachyon w_ϕ, accordingly, decreases gradually with cosmic evolution, and as a result, ${\rm d}w_\phi/{\rm d}\ln a < 0$.

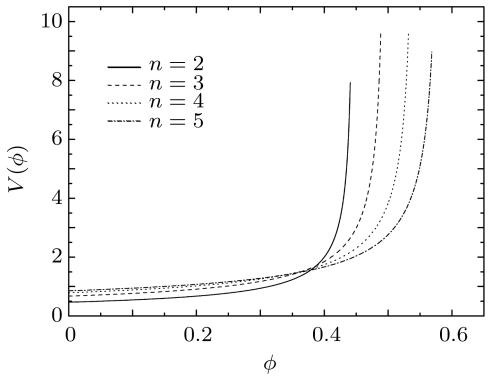


Fig. 2. The reconstructed tachyon potential from the new agegraphic dark energy model, where ϕ is in units of H_0^{-1} and $V(\phi)$ is in $\rho_{\rm c0}$.

Recently Wei[27] considered the cosmological constraints on the new agegraphic dark energy model by using the latest observational data. When combining the 307 Union type Ia supernovae (SNIa), the 32 calibrated Gamma-Ray Bursts (GRBs) at $z > 1.4$, the updated shift parameter R from WMAP 5-year data (WMAP5), and the distance parameter A of the measurement of the baryon acoustic oscillation (BAO) peak in the distribution of SDSS luminous red galaxies with the updated scalar spectral index $n_{\rm s}$ from WMAP5, the fitting for the new agegraphic dark energy model gives the parameter constraint in 1σ: $n = 2.802^{+0.092}_{-0.090}$, with $\chi^2_{\rm min} = 336.061$. According to Eqs. (19)–(21), the reconstructed tachyon potential $V(\phi)$ and field $\phi(z)$ are plotted in Fig. 4, with the cases of $n = 2.802^{+0.092}_{-0.090}$.

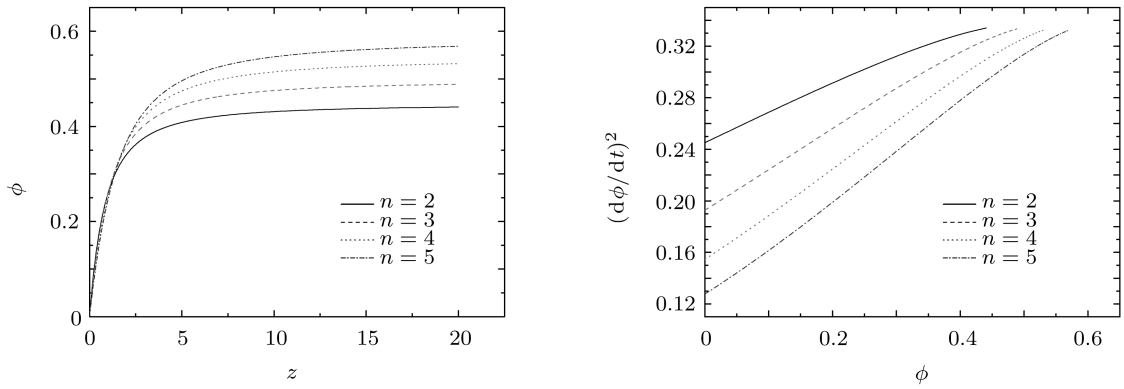


Fig. 3. The dynamics of the tachyon scalar-field, reconstructed according to the evolution of the new agegraphic dark energy. Left panel: the evolution of the tachyon field $\phi(z)$, where ϕ is in units of H_0^{-1}; right panel: the kinetic energy density as a function of scalar-field, namely $\dot{\phi}^2(\phi)$.

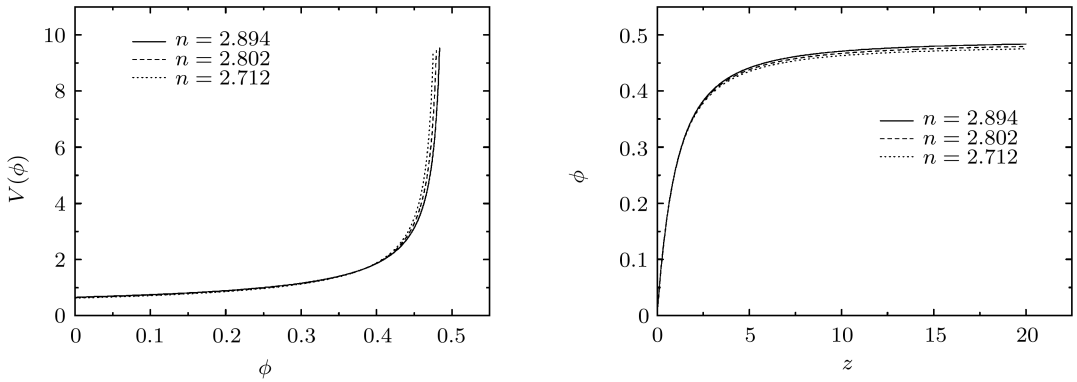


Fig. 4. Reconstruction of the tachyon model, according to the evolution of the new agegraphic dark energy. Here we take $n = 2.802^{+0.092}_{-0.090}$, from the cosmological constraints on the new agegraphic dark energy.

In summary, we suggest a correspondence between the new agegraphic dark energy scenario and the tachyon model in this paper. The new agegraphic dark energy model was proposed by Wei and Cai,[18] based on the Károlyházy uncertainty relation, which arises from quantum mechanics together with general relativity. We adopt the viewpoint that the scalar field models of dark energy are effective theories of an underlying theory of dark energy. If we regard the scalar-field model as an effective description of such a theory, we should be capable of using the scalar-field model to mimic the evolving behaviour of the new agegraphic dark energy and reconstructing this scalar-field model according to the evolutionary behaviour of new agegraphic dark energy. We show that the new agegraphic dark energy can be completely described by the tachyon in a certain way. A correspondence between the new agegraphic dark energy and the tachyon field has been established, and both the tachyon potential and the dynamics of the tachyon field have been reconstructed.

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