Interacting agegraphic tachyon model of dark energy

Ahmad Sheykhi *

Department of Physics, Shahid Bahonar University, P.O. Box 76175, Kerman, Iran
Research Institute for Astronomy and Astrophysics of Maragha (RIAAM), Maragha, Iran

Scalar-field dark energy models like tachyon are often regarded as an effective description of an underlying theory of dark energy. In this Letter, we implement the interacting agegraphic dark energy models with tachyon field. We demonstrate that the interacting agegraphic evolution of the universe can be described completely by a single tachyon scalar field. We thus reconstruct the potential as well as the dynamics of the tachyon field according to the evolutionary behavior of interacting agegraphic dark energy.

I. INTRODUCTION

A great variety of cosmological observations, direct and indirect, reveal that our universe is currently experiencing a phase of accelerated expansion [1]. A component which causes cosmic acceleration is usually dubbed dark energy which constitute a major puzzle of modern cosmology. The most obvious theoretical candidate of dark energy is the cosmological constant. Though, it suffers the so-called fine-tuning and cosmic-coincidence problems. Among different candidates for probing the nature of dark energy, the holographic dark energy model arose a lot of enthusiasm recently [2, 3, 4, 5, 6, 7]. This model is motivated from the holographic hypothesis [8] and has been tested and constrained by various astronomical observations [9, 10]. However, there are some difficulties in holographic dark energy model. Choosing the event horizon of the universe as the length scale, the holographic dark energy gives the observation value of dark energy in the universe and can drive the universe to an accelerated expansion phase. But an obvious drawback concerning causality appears in this proposal. Event horizon is a global concept of spacetime; existence of event horizon of the universe depends on future evolution of the universe; and event horizon exists only for universe with forever accelerated expansion. In addition, more recently, it has been argued that this proposal might be in contradiction to the age of some old high redshift objects, unless a lower Hubble parameter is considered [11].

An interesting proposal to explore the nature of dark energy within the framework of quantum gravity is a so-called agegraphic dark energy (ADE). This model takes into account the Heisenberg...
uncertainty relation of quantum mechanics together with the gravitational effect in general relativity. The ADE model assumes that the observed dark energy comes from the spacetime and matter field fluctuations in the universe [12, 13, 14]. Since in ADE model the age of the universe is chosen as the length measure, instead of the horizon distance, the causality problem in the holographic dark energy is avoided. The agegraphic models of dark energy have been examined and constrained by various astronomical observations [15, 16, 17]. Although going along a fundamental theory such as quantum gravity may provide a hopeful way towards understanding the nature of dark energy, it is hard to believe that the physical foundation of ADE is convincing enough. Indeed, it is fair to say that almost all dynamical dark energy models are settled at the phenomenological level, neither holographic dark energy model nor ADE model is exception. Though, under such circumstances, the models of holographic and ADE, to some extent, still have some advantage comparing to other dynamical dark energy models because at least they originate from some fundamental principles in quantum gravity.

On the other hand, among the various candidates to explain the accelerated expansion, the rolling tachyon condensates in a class of string theories may have interesting cosmological consequences. The tachyon is an unstable field which has became important in string theory through its role in the Dirac-Born-Infeld action which is used to describe the D-brane action [18, 19]. It has been shown [20] that the decay of D-branes produces a pressureless gas with finite energy density that resembles classical dust. The effective Lagrangian for the tachyon field is described by

\[ L = -V(\phi) \sqrt{1 - g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi}, \]  

(1)

where \( V(\phi) \) is the tachyon potential. The corresponding energy momentum tensor for the tachyon field can be written in a perfect fluid form

\[ T_{\mu\nu} = (\rho_\phi + p_\phi) u_\mu u_\nu - p_\phi g_{\mu\nu}, \]  

(2)

where \( \rho_\phi \) and \( p_\phi \) are, respectively, the energy density and pressure of the tachyon and the velocity \( u_\mu \) is

\[ u_\mu = \frac{\partial_\mu \phi}{\sqrt{\partial_\nu \phi \partial^\nu \phi}}. \]  

(3)

A rolling tachyon has an interesting equation of state whose parameter smoothly interpolates between \(-1\) and 0 [21]. Thus, tachyon can be realized as a suitable candidate for the inflation at high energy [22] as well as a source of dark energy depending on the form of the tachyon potential [23]. Therefore it becomes meaningful to reconstruct tachyon potential \( V(\phi) \) from some
dark energy models possessing some significant features of the quantum gravity theory, such as holographic and ADE models. It was demonstrated that dark energy driven by tachyon, decays to cold dark matter in the late accelerated universe and this phenomenon yields a solution to cosmic coincidence problem [24]. The investigations on the reconstruction of the tachyon potential \( V(\phi) \) in the framework of holographic dark energy have been carried out in [25]. In the absence of the interaction between ADE and dark matter, the connection between tachyon field and the new ADE model has also been established in [26].

In the present Letter, we would like to extend the study to the case where both components- the pressureless dark matter and the ADE- do not conserve separately but interact with each other. Given the unknown nature of both dark matter and dark energy there is nothing in principle against their mutual interaction and it seems very special that these two major components in the universe are entirely independent [27, 28, 29]. We shall establish a correspondence between the interacting ADE scenarios and the tachyon scalar field in a non-flat universe. Although it is believed that our universe is flat, a contribution to the Friedmann equation from spatial curvature is still possible if the number of e-foldings is not very large [4]. Besides, some experimental data has implied that our universe is not a perfectly flat universe and recent papers have favored the universe with spatial curvature [30]. We suggest the agegraphic description of the tachyon dark energy in a universe with spacial curvature and reconstruct the potential and the dynamics of the tachyon scalar field which describe the tachyon cosmology. The plan of the work is as follows. In the next section we associate the original ADE with the tachyon field. In section III we establish the correspondence between the new model of interacting ADE and the tachyon dark energy. The last section is devoted to conclusions.

II. TACHYON RECONSTRUCTION OF THE ORIGINAL ADE

We consider the Friedmann-Robertson-Walker (FRW) universe which is described by the line element

\[
 ds^2 = dt^2 - a^2(t) \left( \frac{dr^2}{1 - kr^2} + r^2 d\Omega^2 \right),
\]

where \( a(t) \) is the scale factor, and \( k \) is the curvature parameter with \( k = -1, 0, 1 \) corresponding to open, flat, and closed universes, respectively. A closed universe with a small positive curvature (\( \Omega_k \simeq 0.01 \)) is compatible with observations [30]. The first Friedmann equation takes the form

\[
 H^2 + \frac{k}{a^2} = \frac{1}{3m_p^2} (\rho_m + \rho_D). \tag{5}
\]
We define, as usual, the fractional energy densities such as
\[
\Omega_m = \frac{\rho_m}{3m_p^2H^2}, \quad \Omega_D = \frac{\rho_D}{3m_p^2H^2}, \quad \Omega_k = \frac{k}{H^2a^2},
\] (6)
thus, the Friedmann equation can be written
\[
\Omega_m + \Omega_D = 1 + \Omega_k. \quad (7)
\]

We adopt the viewpoint that the scalar field models of dark energy are effective theories of an underlying theory of dark energy. The energy density and pressure for the tachyon scalar field can be written as
\[
\rho_\phi = -T_0^0 = \frac{V(\phi)}{\sqrt{1 - \dot{\phi}^2}}, \quad (8)
\]
\[
p_\phi = T_i^i = -V(\phi)\sqrt{1 - \dot{\phi}^2}. \quad (9)
\]
Consequently the equation of state of the tachyon is given by
\[
w_\phi = \frac{p_\phi}{\rho_\phi} = \dot{\phi}^2 - 1. \quad (10)
\]
From Eq. (10) we see that irrespective of the steepness of the tachyon potential, we have always 
\[-1 < w_\phi < 0. \] This implies that the tachyon field cannot realize the equation of state crossing 
\[-1. \]
Next we intend to implement the interacting original ADE models with tachyon scalar field.
Let us first review the origin of the ADE model. Following the line of quantum fluctuations of spacetime, Karolyhazy et al. [31] argued that the distance \(t\) in Minkowski spacetime cannot be known to a better accuracy than \(\delta t = \beta t^{2/3}t^{1/3}\) where \(\beta\) is a dimensionless constant of order unity.
Based on Karolyhazy relation, Maziashvili discussed that the energy density of metric fluctuations of the Minkowski spacetime is given by \[32\]
\[
\rho_D \sim \frac{1}{t_p^{2/3}t^{1/3}} \sim \frac{m_p^2}{t^2}, \quad (11)
\]
where \(t_p\) is the reduced Planck time and \(t\) is a proper time scale. In the original ADE model Cai [12] proposed the dark energy density of the form \[11\] where \(t\) is chosen to be the age of the universe
\[
T = \int_0^a \frac{da}{Ha}, \quad (12)
\]
Thus, he wrote down the energy density of the original ADE as \[12\]
\[
\rho_D = \frac{3n^2m_p^2}{T^2}, \quad (13)
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 space-time, and so on. The dark energy density (13) has the same form as the holographic dark energy, but the length measure is chosen to be the age of the universe instead of the horizon radius of the universe. Thus the causality problem in the holographic dark energy is avoided. Combining Eqs. (6) and (13), we get

$$\Omega_D = \frac{n^2}{H^2T^2}. \quad (14)$$

The total energy density is $\rho = \rho_m + \rho_D$, where $\rho_m$ and $\rho_D$ are the energy density of dark matter and dark energy, respectively. The total energy density satisfies a conservation law

$$\dot{\rho} + 3H(\rho + p) = 0. \quad (15)$$

However, since we consider the interaction between dark matter and dark energy, $\rho_m$ and $\rho_D$ do not conserve separately; they must rather enter the energy balances

$$\dot{\rho}_m + 3H\rho_m = Q, \quad (16)$$

$$\dot{\rho}_D + 3H\rho_D(1 + w_D) = -Q. \quad (17)$$

Here $w_D$ is the equation of state parameter of ADE and $Q$ denotes the interaction term and can be taken as $Q = 3b^2H\rho$ with $b^2$ being a coupling constant [33]. Taking the derivative with respect to the cosmic time of Eq. (13) and using Eq. (14) we get

$$\dot{\rho}_D = -2H\sqrt{\Omega_D} \frac{n}{n} \rho_D. \quad (18)$$

Inserting this relation into Eq. (17), we obtain the equation of state parameter of the original ADE in non-flat universe

$$w_D = -1 + 2\frac{2}{3n} \sqrt{\Omega_D} - \frac{b^2}{\Omega_D}(1 + \Omega_k). \quad (19)$$

Differentiating Eq. (14) and using relation $\dot{\Omega}_D = \Omega_D' H$, we reach

$$\Omega_D' = \Omega_D \left( -2 \frac{\dot{H}}{H^2} \frac{\Omega_D}{2}\sqrt{\Omega_D} \right), \quad (20)$$

where the dot and the prime stand for the derivative with respect to the cosmic time and the derivative with respect to $x = \ln a$, respectively. Taking the derivative of both side of the Friedman equation (5) with respect to the cosmic time, and using Eqs. (7), (13), (14) and (16), it is easy to show that

$$\frac{\dot{H}}{H^2} = -\frac{3}{2} (1 - \Omega_D) - \frac{\Omega_D^{3/2}}{n} + \frac{\Omega_k}{2} + \frac{3}{2} b^2(1 + \Omega_k). \quad (21)$$
Substituting this relation into Eq. (20), we obtain the equation of motion for the original ADE

\[ \Omega_D' = \Omega_D \left[ (1 - \Omega_D) \left( 3 - \frac{2}{n} \sqrt{\frac{\Omega_D}{2}} \right) - 3b^2 (1 + \Omega_k) + \Omega_k \right]. \]  (22)

From the first Friedmann equation (5) as well as Eqs. (7), (16) and (17), we obtain

\[ H = H_0 \sqrt{\frac{1 + \Omega_{k0}}{1 + \Omega_k}} \exp \left[ -\frac{3}{2} \int_{a_0}^a (1 + w_D) \frac{da}{a} \right]. \]  (23)

Now we suggest a correspondence between the original ADE and tachyon scalar field namely, we identify \( \rho_\phi \) with \( \rho_D \). Using relation \( \rho_\phi = \rho_D = 3m_p^2 H^2 \Omega_D \) and Eqs. (8), (10) and (19), we can find

\[ V(\phi) = \rho_\phi \sqrt{1 - \phi^2} = 3m_p^2 H^2 \Omega_D \left( 1 - \frac{2}{3n} \sqrt{\frac{\Omega_D}{2}} + \frac{b^2}{\Omega_D} (1 + \Omega_k) \right)^{1/2}, \]  (24)

\[ \dot{\phi} = \pm \sqrt{1 + w_D} \left( \frac{2}{3n} \sqrt{\frac{\Omega_D}{2}} - \frac{b^2}{\Omega_D} (1 + \Omega_k) \right)^{1/2}. \]  (25)

Using relation \( \dot{\phi} = H \phi' \), we get

\[ \phi' = H^{-1} \left( \frac{2}{3n} \sqrt{\frac{\Omega_D}{2}} - \frac{b^2}{\Omega_D} (1 + \Omega_k) \right)^{1/2}. \]  (26)

Consequently, we can easily obtain the evolutionary form of the tachyon field by integrating the above equation

\[ \phi(a) - \phi(a_0) = \int_{a_0}^a \frac{1}{Ha} \sqrt{\frac{2}{3n} \sqrt{\Omega_D}} - \frac{b^2}{\Omega_D} (1 + \Omega_k) \, da, \]  (27)

where \( a_0 \) is the value of the scale factor at the present time \( t_0 \), \( H \) is given by Eq. (23) and \( \Omega_D \) can be extracted from Eq. (22). The above equation can also be written in the following form

\[ \phi(t) - \phi(t_0) = \int_{t_0}^t \sqrt{\frac{2}{3n} \sqrt{\Omega_D}} - \frac{b^2}{\Omega_D} (1 + \Omega_k) \, dt'. \]  (28)

Therefore, we have established an interacting agegraphic tachyon dark energy model and reconstructed the potential and the dynamics of the tachyon field. It is worth noting that if one omits \( \Omega_D \) between Eqs. (24) and (27), one can obtain \( V = V(\phi) \). Unfortunately, this cannot be done analytically for the above general solutions. Let us consider, as an example, the matter-dominated epoch where \( a \ll 1 \) and \( \Omega_D \ll 1 \). In this case Eq. (22) with \( \Omega_k \ll 1 \) approximately becomes

\[ \frac{d\Omega_D}{da} \simeq \frac{\Omega_D}{a} \left( 3 - \frac{2}{n} \sqrt{\frac{\Omega_D}{2}} - 3b^2 \right), \]  (29)

Solving the above equation we find

\[ \Omega_D = \frac{9n^2}{4} (1 - b^2)^2. \]  (30)
Substituting this relation into Eq. (19), we obtain

\[ w_D = -b^2 \left( 1 + \frac{4}{9n^2(1 - b^2)^2} \right). \]  

(31)

In this case for \( \Omega_k \ll 1 \), Eq. (23) can be integrated. The result is

\[ H = H_0a^{-3(1+w_D)/2}. \]  

(32)

Combining Eqs. (30) and (32) with (27) we find

\[ \phi = \frac{2a^{3(1+w_D)/2}}{3H_0 \sqrt{1 + w_D}}, \]  

(33)

up to a constant of integration. From this equation we get

\[ a = \left( \frac{9(1 + w_D)\phi^2 H_0^2}{4} \right)^{1/(1+w_D)}. \]  

(34)

Finally, combining Eqs. (30), (31), (34) with Eq. (24) we reach

\[ V(\phi) = \frac{-9m_p^2 (-1 + b^2)^3 n^3 b \sqrt{-9 n^2 + 18 n^2 b^2 - 9 n^2 b^4 - 4}}{(-9 n^2 + 27 n^2 b^2 - 27 n^2 b^4 + 9 n^2 b^6 + 4 b^2) \phi^2}. \]  

(35)

III. TACHYON RECONSTRUCTION OF THE NEW ADE

To avoid some internal inconsistencies in the original ADE model, the so-called “new agegraphic dark energy” was proposed, where the time scale is chosen to be the conformal time \( \eta \) instead of the age of the universe \( \tau \). The new ADE contains some new features different from the original ADE and overcome some unsatisfactory points. For instance, the original ADE suffers from the difficulty to describe the matter-dominated epoch while the new ADE resolved this issue \[13\]. The energy density of the new ADE can be written

\[ \rho_D = \frac{3n^2 m_p^2}{\eta^2}, \]  

(36)

where the conformal time \( \eta \) is given by

\[ \eta = \int \frac{dt}{a} = \int_{a_0}^{a} \frac{da}{Ha^2}. \]  

(37)

The fractional energy density of the new ADE is now expressed as

\[ \Omega_D = \frac{\eta^2}{H^2 \eta^2}. \]  

(38)

Taking the derivative with respect to the cosmic time of Eq. (36) and using Eq. (38) we get

\[ \dot{\rho}_D = -2H \sqrt{\Omega_D} \rho_D. \]  

(39)
Inserting this relation into Eq. (17) we obtain the equation of state parameter of the new ADE
\[ w_D = -1 + \frac{2}{3a} \sqrt{\Omega_D} - \frac{b^2}{\Omega_D} (1 + \Omega_k). \] (40)
The evolution behavior of the new ADE is now given by
\[ \Omega_D' = \Omega_D \left[ (1 - \Omega_D) \left( 3 - \frac{2}{na} \sqrt{\Omega_D} \right) - 3b^2 (1 + \Omega_k) + \Omega_k \right]. \] (41)
Next, we reconstruct the new agegraphic tachyon dark energy model, connecting the tachyon scalar field with the new ADE. Using Eqs. (38) and (40) one can easily show that the tachyon potential and kinetic energy term take the following form
\[ V(\phi) = 3m^2 H^2 \Omega_D \left( 1 - \frac{2}{3na} \sqrt{\Omega_D} + \frac{b^2}{\Omega_D} (1 + \Omega_k) \right)^{1/2}, \] (42)
\[ \dot{\phi} = \left( \frac{2}{3na} \sqrt{\Omega_D} - \frac{b^2}{\Omega_D} (1 + \Omega_k) \right)^{1/2}. \] (43)
We can also rewrite Eq. (43) as
\[ \phi' = H^{-1} \left( \frac{2}{3na} \sqrt{\Omega_D} - \frac{b^2}{\Omega_D} (1 + \Omega_k) \right)^{1/2}. \] (44)
Therefore the evolution behavior of the tachyon field can be obtained by integrating the above equation
\[ \phi(a) - \phi(a_0) = \int_{a_0}^{a} \frac{1}{H a} \sqrt{\frac{2}{3na} \sqrt{\Omega_D} - \frac{b^2}{\Omega_D} (1 + \Omega_k)} \, da, \] (45)
or in another way
\[ \phi(t) - \phi(t_0) = \int_{t_0}^{t} \sqrt{\frac{2}{3na} \sqrt{\Omega_D} - \frac{b^2}{\Omega_D} (1 + \Omega_k)} \, dt'. \] (46)
where \( \Omega_D \) is now given by Eq. (41). In this way we connect the interacting new ADE with a tachyon field and reconstruct the potential and the dynamics of the tachyon field which describe tachyon cosmology.

IV. CONCLUSIONS

Among the various candidates to play the role of the dark energy, tachyon has emerged as a possible source of dark energy for a particular class of potentials [23]. In this Letter, we have associated the interacting ADE models with a tachyon field which describe the tachyon cosmology in a non-flat universe. The ADE models take into account the Heisenberg uncertainty relation
of quantum mechanics together with the gravitational effect in general relativity. These models assume that the observed dark energy comes from the spacetime and matter field fluctuations in the universe. Therefore, agegraphic scenarios may possess some significant features of an underlying theory of dark energy. We have demonstrated that the agegraphic evolution of the universe can be described completely by a tachyon scalar field in a certain way. We have adopted the viewpoint that the scalar field models of dark energy are effective theories of an underlying theory of dark energy. Thus, we should be capable of using the scalar field model to mimic the evolving behavior of the interacting ADE and reconstructing this scalar field model. We have reconstructed the potential and the dynamics of the tachyon scalar field according to the evolutionary behavior of the interacting agegraphic dark energy models.

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