Interacting agegraphic quintessence dark energy in non-flat universe

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We suggest a correspondence between interacting agegraphic dark energy models and the quintessence scalar field in a non-flat universe. We demonstrate that the agegraphic evolution of the universe can be described completely by a single quintessence scalar field. Then, we reconstruct the potential of the interacting agegraphic quintessence dark energy as well as the dynamics of the scalar field according to the evolution of the agegraphic dark energy.

I. INTRODUCTION

It is a general belief that our universe is currently experiencing a phase of accelerated expansion\cite{1}. Missing energy component with negative pressure which is responsible for this expansion constitute a major puzzle of modern cosmology. Despite the theoretical difficulties in understanding dark energy, independent observational evidence for its existence is impressively robust. Among the various candidates to explain the accelerated expansion, the cosmological constant with $w = -1$ is located at a central position. Though, it suffers the so-called fine-tuning and cosmic coincidence problems. In quintessence\cite{2} and Chaplygin gas\cite{3} $w$ always stays bigger than $-1$. The phantom models of dark energy have $w < -1$\cite{4}. However, following the more accurate data analysis, a more dramatic result appears showing that the time varying dark energy gives a better fit than a cosmological constant and in particular, $w$ can cross $-1$ from above to below\cite{5}.

An interesting attempt for probing the nature of dark energy within the framework of quantum gravity is the holographic dark energy. This proposal, that arose a lot of enthusiasm recently\cite{6-11}, is motivated from the holographic hypothesis\cite{12} and has been tested and constrained by various astronomical observations\cite{13}. 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\cite{14}. Another proposal to probe the nature of dark energy within the framework of quantum gravity is a so-called agegraphic dark energy (ADE). This model is based on the uncertainty relation of quantum mechanics together with the gravitational effect in general relativity. Following the line of quantum fluctuations of spacetime, Karolyhazy et al.\cite{15} argued that the distance $t$ in Minkowski spacetime cannot be known to a better accuracy than $\delta t = \beta t^{2/3} l^{1/3}$ 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\cite{16}

$$\rho_D \sim \frac{1}{t_p^{2/3}} \sim \frac{m_p^4}{l_p^2}$$   \hspace{1cm} (1)

where $t_p$ is the reduced Planck time. We use the units $c = \hbar = k_b = 1$ throughout this work. Therefore one has $l_p = t_p = 1/m_p$ with $l_p$ and $m_p$ are the reduced Planck length and mass, respectively. The agegraphic dark energy model assumes that the observed dark energy comes from the spacetime and matter field fluctuations in the universe\cite{17-19}. Since in agegraphic dark energy 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\cite{20-22}. 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 agegraphic dark energy 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 agegraphic dark energy model is exception. Though, under such circumstances, the models of holographic and agegraphic dark energy, 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. We thus may as well view that this class of models possesses some features of an underlying theory of dark energy.

On the other hand, the scalar field model is an effective description of an underlying theory of dark energy. Scalar fields naturally arise in particle physics including supersymmetric field theories and string/M theory. Therefore, scalar field is expected to reveal the dynamical mechanism and the nature of dark energy. However, although fundamental theories such as string/M theory do provide a number of possible candidates for scalar fields, they do not uniquely predict its potential $V(\phi)$. Therefore it becomes meaningful to reconstruct $V(\phi)$ from some dark energy models possessing some significant features of the quantum gravity theory, such as holographic and agegraphic dark energy model. The investigations on the reconstruction of the potential $V(\phi)$ in the framework of holographic dark energy have been carried out in [23]. In the absence of the interaction between agegraphic dark energy and dark matter, the quintessence reconstruction of the agegraphic dark energy models have been established [24].

In this paper we intend to generalize the study to the case where both components— the pressureless dark matter and the agegraphic dark energy— 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 [25–27]. We shall establish a correspondence between the interacting agegraphic dark energy scenarios and the quintessence scalar field. We suggest the agegraphic description of the quintessence dark energy in a universe with spacial curvature and reconstruct the potential and the dynamics of the quintessence scalar field which describe the quintessence cosmology.

This paper is outlined as follows. In the next section we demonstrate a correspondence between the original agegraphic and quintessence dark energy model. In section III we establish the correspondence between the new model of interacting agegraphic dark energy and the quintessence dark energy. The last section is devoted to conclusions.

II. QUINTESSENCE RECONSTRUCTION OF ORIGINAL ADE

We assume the agegraphic quintessence dark energy is accommodated in the Friedmann-Robertson-Walker (FRW) universe which is described by the line element

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

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 [28]. The corresponding Friedmann equation takes the form

$$H^2 + \frac{k}{a^2} = \frac{1}{3m_p^2} (\rho_m + \rho_D).$$

We introduce, as usual, the fractional energy densities such as

$$\Omega_m = \frac{\rho_m}{3m_p^2 H^2}, \quad \Omega_D = \frac{\rho_D}{3m_p^2 H^2}, \quad \Omega_k = \frac{k}{H^2 a^2},$$

thus, the Friedmann equation can be written

$$\Omega_m + \Omega_D = 1 + \Omega_k.$$

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 quintessence scalar field can be written as

$$\rho_\phi = \frac{1}{2} \dot{\phi}^2 + V(\phi),$$

$$p_\phi = \frac{1}{2} \dot{\phi}^2 - V(\phi),$$

Then, we can easily obtain the scalar potential and the kinetic energy term as

$$V(\phi) = \frac{1 - w_D}{2} \rho_\phi,$$

$$\dot{\phi}^2 = (1 + w_D) \rho_\phi.$$
Now we are focusing on the reconstruction of the original agegraphic quintessence model of dark energy. The original agegraphic dark energy density has the form (1) where $t$ is chosen to be the age of the universe

$$ T = \int_t^0 \frac{da}{H a}. $$

Thus, the energy density of the original agegraphic dark energy is given by (17)

$$ \rho_D = \frac{3n^2m_p^2}{T^2}, $$

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 (since the energy density is derived for Minkowski space-time), and so on. The dark energy density (11) 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. (4) and (11), we get

$$ \Omega_D = \frac{n^2}{H^2T^2}. $$

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

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

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

$$ \dot{\rho}_m + 3H\rho_m = Q, $$

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

Here $w_D$ is the equation of state parameter of agegraphic dark energy and $Q$ denotes the interaction term and can be taken as $Q = 3b^2H\rho$ with $b^2$ being a coupling constant. This expression for the interaction term was first introduced in the study of the suitable coupling between a quintessence scalar field and a pressureless cold dark matter field [29, 30]. In the context of holographic dark energy model, this form of interaction was derived from the choice of Hubble scale as the IR cutoff [31]. Taking the derivative with respect to the cosmic time of Eq. (11) and using Eq. (12) we get

$$ \dot{\Omega}_D = \frac{n^2}{H^2T^2}. $$

Inserting this relation into Eq. (15), we obtain the equation of state parameter of the original agegraphic dark energy

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

Differentiating Eq. (12) and using relation $\dot{\Omega}_D = \Omega'_D H$, we reach

$$ \Omega'_D = \Omega_D \left( -2\frac{\dot{H}}{H^2} - \frac{2}{n}\sqrt{\Omega_D} \right). $$

where the dot and the prime stand, respectively, for the derivative with respect to the cosmic time and the derivative with respect to $x = \ln a$. Taking the derivative of both side of the Friedman equation (3) with respect to the cosmic time, and using Eqs. (5), (11), (12) and (14), it is easy to show that

$$ \frac{\dot{H}}{H^2} = -\frac{3}{2}(1 - \Omega_D) - \frac{\Omega_D^{3/2}}{n} - \frac{\Omega_k}{2} + \frac{3}{2}b^2(1 + \Omega_k). $$

Substituting this relation into Eq. (18), we obtain the equation of motion of agegraphic dark energy

$$ \Omega'_D = \Omega_D \left[ (1 - \Omega_D) \left( 3 - \frac{2}{n}\sqrt{\Omega_D} \right) - 3b^2(1 + \Omega_k) + \Omega_k \right]. $$
We plot in Figs. 1 and 2 the evolutions of the $w_D$ and $\Omega_D$ of the original ADE with different interacting parameter $b^2$. From Fig. 1 we see that $w_D$ of the agegraphic dark energy can cross the phantom divide. It was argued \[18\] that without interaction ($b^2 = 0$) $w_D$ is always larger than $-1$ and cannot cross the phantom divide. In the presence of the interaction the situation is changed. An interesting observation from Fig. 1 is that $w_D$ crosses the phantom divide from $w_D < -1$ to $w_D > -1$. This makes it distinguishable from many other dark energy models whose $w_D$ can cross the phantom divide. Fig. 2 shows that at the early time $\Omega_D \rightarrow 0$ while at the late time $\Omega_D \rightarrow 1$, that is the ADE dominates as expected.

Now we suggest a correspondence between the original agegraphic dark energy and quintessence scalar field namely, we identify $\rho_\phi$ with $\rho_D$. Using relation $\rho_\phi = \rho_D = 3m_p^2H^2\Omega_D$ and Eq. \[17\] we can rewrite the scalar potential and kinetic energy term as

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

\[21\]
FIG. 3: The reconstruction of the potential $V(\phi)$ for original ADE with different model parameter $n$, where $\phi$ is in unit of $m_p$ and $V(\phi)$ in $\rho_c$. We take here $\Omega_{m0} = 0.28$ and $\Omega_k = 0.01$.

![Graph of V(\phi) for different n values](image)

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

$$\dot{\phi} = m_p H \left( \frac{2}{n} \Omega_D^{3/2} - 3b^2(1 + \Omega_k) \right)^{1/2}.$$  (22)

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

$$\phi' = m_p \left( \frac{2}{n} \Omega_D^{3/2} - 3b^2(1 + \Omega_k) \right)^{1/2}.$$  (23)
Consequently, we can easily obtain the evolutionary form of the field by integrating the above equation

$$\phi(a) - \phi(a_0) = \int_{a_0}^{a} \frac{m_P}{a} \sqrt{\frac{2}{n} \Omega_D^{3/2} - 3b^2(1 + \Omega_k)} da,$$

where $a_0$ is the present value of the scale factor, and $\Omega_D$ is given by Eq. (20). Therefore, we have established an interacting agegraphic quintessence dark energy model and reconstructed the potential of the agegraphic quintessence as well as the dynamics of scalar field.

As one can see from the above equations, the analytical form of the potential $V = V(\phi)$ is hard to be derived due to the complexity of the equations, but we can plot the agegraphic quintessence potential versus $a$ numerically. For simplicity we take $\Omega_k \simeq 0.01$ fixed in the numerical discussion. Besides, $\rho_{c0} = 3m_P^2 H_0^2$ is the present value of the critical energy density of the universe. The reconstructed quintessence potential $V(\phi)$ and the evolutionary form of the field are plotted in Figs. 3-6, where we have taken $\phi(a_0 = 1) = 0$. Selected curves are plotted for the different
model parameter \( n \) with fixed \( \dot{b}^2 \) and different \( \dot{b}^2 \) with fixed \( n \), and the present fractional matter density is chosen to be \( \Omega_{m0} = 0.28 \). From these figures we can see the dynamics of the potential as well as the scalar field explicitly. They also show that the reconstructed quintessence potential is steeper in the early epoch and becomes very flat near today. Consequently, the scalar field \( \phi \) rolls down the potential with the kinetic energy \( \dot{\phi} \) gradually decreasing.

### III. QUINTESSENCE RECONSTRUCTION OF NEW ADE

Soon after the original agegraphic dark energy model was introduced by Cai [17], a new model of agegraphic dark energy was proposed in [18], while the time scale is chosen to be the conformal time \( \eta \) instead of the age of the universe. It is worth noting that the Karolyhazy relation \( \delta t = \beta t_p^{2/3} t^{1/3} \) was derived for Minkowski spacetime \( ds^2 = dt^2 - dx^2 \) [15, 16]. In the case of the FRW universe, we have \( ds^2 = dt^2 - a^2 dx^2 = a^2(d\eta^2 - dx^2) \). Thus, it might be more reasonable to choose the time scale in Eq. (11) to be the conformal time \( \eta \) since it is the causal time in the Penrose diagram of the FRW universe. The new agegraphic dark energy contains some new features different from the original agegraphic dark energy and overcome some unsatisfactory points. For instance, the original agegraphic dark energy suffers from the difficulty to describe the matter-dominated epoch while the new agegraphic dark energy resolved this issue [18]. The energy density of the new agegraphic dark energy can be written

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

(25)

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

\[
\eta = \int \frac{dt}{a} = \int_0^a \frac{da}{Ha^2}.
\]

(26)

The fractional energy density of the new agegraphic dark energy is now given by

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

(27)

Taking the derivative with respect to the cosmic time of Eq. (25) and using Eq. (27) we get

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

(28)

![Figure 7](image.png)  
**FIG. 7**: The evolution of \( w_D \) for new ADE with different interacting parameter \( b^2 \). Here we take \( \Omega_{D0} = 0.72 \) and \( \Omega_k = 0.01 \).
Inserting this relation into Eq. (15) we obtain the equation of state parameter of the new agegraphic dark energy
\[
    w_D = -1 + \frac{2}{3na} \sqrt{\Omega_D} - \frac{b^2}{\Omega_D} (1 + \Omega_k).
\] (29)

The evolution behavior of the new agegraphic dark energy is now given by
\[
    \Omega'_D = \Omega_D \left[ (1 - \Omega_D) \left( 3 - \frac{2}{na} \sqrt{\Omega_D} \right) - 3b^2 (1 + \Omega_k) + \Omega_k \right].
\] (30)

We plot in Figs. 7 and 8 the evolutions of $w_D$ and $\Omega_D$ of the new ADE with different interacting parameter $b^2$. From Fig. 7 we see that $w_D$ of the new ADE can have a transition from $w_D > -1$ to $w_D < -1$. This is in contrast to the
FIG. 10: The reconstruction of the potential $V(\phi)$ for new ADE with different interacting parameter $b^2$, where $\phi$ is in unit of $m_p$ and $V(\phi)$ in $\rho_c$. We take here $\Omega_{m0} = 0.28$.

FIG. 11: The revolution of the scalar-field $\phi(a)$ for new ADE with different interacting parameter $b^2$, where $\phi$ is in unit of $m_p$ and we take here $\Omega_{m0} = 0.28$.

original ADE model. Fig. 8 indicates that at the late time $\Omega_D \to 1$, which is similar to the behaviour of the original ADE.

Next, we reconstruct the new agegraphic quintessence dark energy model, connecting the quintessence scalar field with the new agegraphic dark energy. Using Eqs. (27) and (29) one can easily show that the scalar potential and kinetic energy term take the following form

\begin{equation}
V(\phi) = m_p^2 H^2 \Omega_D \left( 3 - \frac{\sqrt{\Omega_D}}{na} + \frac{3b^2 (1 + \Omega_k)}{\Omega_D} \right),
\end{equation}

\begin{equation}
\dot{\phi} = m_p H \left( \frac{2}{na} \Omega_D^{3/2} - 3b^2 (1 + \Omega_k) \right)^{1/2}.
\end{equation}
FIG. 12: The revolution of the scalar-field $\phi(a)$ for new ADE with different model parameter $n$, where $\phi$ is in unit of $m_p$ and we take here $\Omega_{m0} = 0.28$.

Using Eq. (32), Eq. (31) can be reexpressed as

$$V(\phi) = 3m_p^2H^2\Omega_D \left(1 - \frac{\dot{\phi}^2}{6m_p^2H^2\Omega_D}\right).$$  (33)

We can also rewrite Eq. (32) as

$$\phi' = m_p \left(\frac{2}{n a} \Omega_D^{3/2} - 3b^2(1 + \Omega_k)\right)^{1/2}.$$  (34)

Therefore the evolution behavior of the scalar field can be obtained by integrating the above equation

$$\phi(a) - \phi(a_0) = \int_{a_0}^{a} \frac{m_p}{a} \sqrt{\frac{2}{n a} \Omega_D^{3/2} - 3b^2(1 + \Omega_k)} da,$$  (35)

where $\Omega_D$ is now given by Eq. (30). In this way we connect the interacting agegraphic dark energy with a quintessence scalar field and reconstruct the potential of the agegraphic quintessence. The reconstructed quintessence potential $V(\phi)$ and the evolutionary form of the scalar field are plotted in Figs. 9-12 for different model parameter $n$ with fixed interacting parameter $b^2$, and different $b^2$ with fixed $n$. Here the present fractional matter density is chosen to be $\Omega_{m0} = 0.28$.

IV. CONCLUSIONS

In this paper, we have suggested a correspondence between the interacting agegraphic dark energy scenarios and the quintessence scalar field model in a non-flat universe. We have demonstrated that the agegraphic evolution of the universe can be described completely by a single quintessence scalar field. We have adopted 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 behavior of the interacting agegraphic dark energy and reconstructing this scalar field model according to the evolutionary behavior of agegraphic dark energy. We have also reconstructed the potential of the agegraphic scalar field as well as the dynamics of the quintessence scalar field which describe the quintessence cosmology.
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