Interacting entropy-corrected new agegraphic K-essence, tachyon and dilaton scalar field models in non-flat universe

M. Umar Farooq,1,∗ Muneer A. Rashid,1 and Mubasher Jamil1,†

1Center for Advanced Mathematics and Physics,
National University of Sciences and Technology, Rawalpindi, 46000, Pakistan

Abstract

We present the new agegraphic dark energy model with the help of the quantum corrections to the entropy-area relation in the setup of loop quantum gravity. Employing this new form of dark energy, we investigate the model of interacting dark energy and derive its equation of state (EoS). We study the correspondence between the K-essence, tachyon and dilaton scalar fields with the interacting entropy-corrected new agegraphic dark energy in the non-flat FRW universe. Moreover, we reconstruct the corresponding scalar potentials which describe the dynamics of the scalar field.

∗Electronic address: mfarooq@camp.nust.edu.pk
†Electronic address: mjamil@camp.nust.edu.pk
I. INTRODUCTION

One of the most outstanding developments in the last decade is the discovery that at the current era our universe is undergoing the phase of accelerating expansion \[1\]. “Dark energy”, an unknown exotic vacuum energy responsible for propelling the universe, is one of the deepest mysteries in astrophysics. The dark energy possesses negative pressure \(p < 0\) and positive energy density \(\rho > 0\) which is related by the equation of state \(p = \omega \rho\). Astrophysical data suggests that about two-thirds of the critical energy is stored in the dark energy component apart from dark matter which contains only one third of the critical energy density. One possible source of this cosmic expansion can be explained by the general theory of relativity with the cosmological constant \(\Lambda\). Although the cosmological constant is the most obvious choice, but it suffers from coincidence problem and the fine-tuning problems \[2\]. To overcome these problems, several alternative models have been suggested; among them are dynamical scalar field \(\phi\) with suitably defined scalar field potential \(V(\phi)\) termed as quintessence \[3\], quintom \[4\], k-essence \[5\], tachyon \[6\], phantom \[7\], dilatonic ghost condensate \[8\] to name a few. In addition, there are other proposals on dark energy such as interacting dark energy models \[9\], brane world models \[10\] and Chaplygin gas models \[11\] etc.

In the last few years, the holographic dark energy (HDE) models \[12\] and agegraphic dark energy models \[13\] have received a considerable interest. Holographic principle is a speculative conjecture about proposed quantum theories of gravities. According to holographic principle, the information contained in a volume may be described by a theory that lies on the boundary of that space \[14\]. In the study of thermodynamics of the black hole, there is a maximum entropy in a box of size \(L\), known as the Bekenstein Hawking entropy bound \(S \sim m_p^2 L^2\) which scales as the area of the box \(A \sim L^2\). To avoid the breakdown of quantum field theory in the framework of quantum gravity, Cohen et al \[15\] proposed that the entropy for an effective theory should satisfy \(L^3 \Lambda^3 \leq S^{3/4} \leq (m_p^2 L)^{3/2}\). Here \(L\) associated with the size of a region which gives an infra-red cut-off while \(\Lambda\) corresponds to the ultra-violet cut-off. The last expression can be transformed to \(\rho_\Lambda = 3n^2 m_p^2 L^2\), where \(3n^2\) is for convenience and \(m_p = 1/\sqrt{8\pi G}\) is the Plank mass. In Einstein theory of gravity, the definition of holographic dark energy requires the entropy-area relationship \(S \sim A \sim L^2\), where \(A\) is the area of the horizon. However in the context of loop quantum gravity (LQG), this
entropy-area relationship gets modified from the inclusion of quantum effects. The quantum corrections provided to the entropy-area relationship facilitates us to obtain correction in the Hilbert action and vise versa [16]. The corrected entropy is

\[ S = \frac{A}{4G} + \tilde{\gamma} \ln \left( \frac{A}{4G} \right) + \tilde{\beta}, \tag{1} \]

where \( \tilde{\gamma} \) and \( \tilde{\beta} \) are constants of order unity. The exact values of these parameters are unknown and still a matter of debate. These corrections usually come into view in the black hole entropy in LQG due to thermal and quantum fluctuations [17]. The entropy-corrected holographic dark energy (ECHDE) is given by [18]

\[ \rho_\Lambda = 3n^2m_p^2L^{-2} + \gamma L^{-4} \ln(m_p^2L^2) + \beta L^{-4}, \tag{2} \]

where \( \tilde{\gamma} \) and \( \tilde{\beta} \) are dimensionless constants of order unity. Clearly if we put \( \tilde{\gamma} = \tilde{\beta} = 0 \), we arrive at the holographic dark energy model.

Though HDE is considered to be the most promising candidate for dark energy, but there are some difficulties appear in HDE model. Choosing the future event horizon of the universe as the length scale, the HDE model does not contradict to the observed value of dark energy in the universe and can propel the universe to an accelerated expansion phase. However, the current properties of the dark energy determined by the future evolution of the universe might violate causality. Moreover, it has been argued that this model might be in contradiction to the age of the universe [19].

Recently, Cai [13] has proposed a model, dubbed “agegraphic dark energy” (ADE) based on Karolyhazy uncertainty relation \( \delta t = \lambda t_p^{2/3} T^{1/3} \) [20], \( \lambda \) is a numerical factor of order one and \( t_p \) is the Plank time. Following the Karolyhazy relation Maziashvili argued that the energy density of metric fluctuation of Minkowski spacetime can be written as \( \rho_\Lambda \sim \frac{1}{t_p^{2+\tau^2}} \sim \frac{m_p^2}{\tau^2} \), where the time scale \( \tau \) is chosen to be the age of the universe \( T = \int_0^\tau \frac{da}{H} \) and the energy density of the agegraphic dark energy can be expressed as \( \rho_\Lambda = 3n^2m_p^2T^{-2} \) [13]. Since in the ADE model the age of the universe is taken as the length measure instead of the horizon distance, so the causality problem that appears in the HDE model can be avoided. However, the ADE model might contain an inconsistency [21]. So to overcome this problem, soon after the original ADE model, the authors [22] proposed an alternative model of dark energy so called the “new agegraphic dark energy” (NADE) and its density energy is defined by

\[ \rho_\Lambda = 3n^2m_p^2\eta^{-2}, \tag{3} \]
where $\eta$ is conformal time of the FRW-universe and is written as

$$\eta = \int \frac{dt}{a} = \int_0^a \frac{da}{Ha^2}. \quad (4)$$

In this paper, we extend our study of NADE from the inclusion of quantum corrections to the entropy-area relation. We investigate the entropy-corrected version of the interacting NADE model so called the entropy-corrected new agegraphic dark energy (ECNADE) and see its effects in the non-flat universe. The plan of the work is as follows. In Section 2, we study the ECNADE model in a non-flat Friedmann-Robertson-Walker (FRW) universe and derive its equation of state. In Section 3, we present a correspondence between the ECNADE and the K-essence, tachyon and dilaton scalar fields. In each case, we reconstruct the potential and dynamics for these scalar fields which depict the accelerated expansion.

**II. INTERACTING ECNADE MODEL**

We assume the background to be a spatially homogeneous and isotropic FRW spacetime, given by

$$ds^2 = -dt^2 + a^2(t) \left[ \frac{dr^2}{1 - kr^2} + r^2(d\theta^2 + \sin^2 \theta d\varphi^2) \right]. \quad (5)$$

Here $a(t)$ is the dimensionless scale factor which is an arbitrary function of time and $k$ represents the curvature parameter which has dimensions of length$^{-2}$. For the values $k = -1, 0, 1$, the above metric represents the spatially open, flat and closed FRW universe respectively. The first Friedmann equation for the non-flat FRW-spacetime containing the dark energy and dark matter is

$$H^2 + \frac{k}{a^2} = \frac{1}{3M_p^2}[\rho_\Lambda + \rho_m]. \quad (6)$$

where $M_p^2 = (8\pi G)^{-1}$ is modified Planck mass. Here $H = \dot{a}/a$ is the Hubble constant while $\rho_\Lambda$ and $\rho_m$ represent the energy densities of dark energy and matter respectively. Let us define the dimensionless energy density parameters as

$$\Omega_m = \frac{\rho_m}{\rho_{cr}} = \frac{\rho_m}{3M_p^2H^2}, \quad \Omega_\Lambda = \frac{\rho_\Lambda}{\rho_{cr}} = \frac{\rho_\Lambda}{3M_p^2H^2}, \quad \Omega_k = \frac{k}{(aH)^2}. \quad (7)$$

With the help of these parameters, the Friedmann Eq. (6) takes the form

$$1 + \Omega_k = \Omega_\Lambda + \Omega_m. \quad (8)$$
In the setup of LQG, we would like to consider ECNADE whose length $L$ in Eq. (2) is taken to be the conformal time $\eta$ given by (4). So the density of the ECNADE can be written as

$$\rho_\Lambda = 3n^2m_p^2\eta^{-2} + \gamma\eta^{-4}\ln(m_p^2\eta^2) + \beta\eta^{-4},$$

(9)

where $\gamma$ and $\beta$ are dimensionless constants of order one. Employing the relationship $\Omega_\Lambda = \frac{\rho_\Lambda}{3H^2m_p^2}$, we get

$$\Omega_\Lambda = \sqrt{\frac{3n^2m_p^2 + \gamma\eta^{-2}\ln(m_p^2\eta^2) + \beta\eta^{-2}}{3m_p^2H^2\eta^2}}.$$

(10)

Let us assume an interaction $Q = \Gamma\rho_\Lambda$ between ECNADE and the cold dark matter (CDM) having $\omega_m = 0$. The resulting energy conservation equations for ECNADE and CDM are

$$\dot{\rho}_\Lambda + 3H(\rho_\Lambda + p_\Lambda) = -Q,$$

(11)

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

(12)

Here overdot represents the differentiation with respect to cosmic time $t$. These interacting models describe an energy flow between the dark energy and dark matter so that no component shows energy conservation independently. If two species are present in dominant form, they are definitely supposed to interact. We choose $\Gamma = 3b^2H\left(\frac{1+\Omega_k}{\Omega_\Lambda}\right)$ as the decay rate of the ECNADE component into CDM with a coupling constant $b^2$. The importance of interacting model also emerges as it is good fit to the expansion history of the universe as determined by the Supernovae and cosmic microwave background [1].

Differentiate Eq. (9) with respect to time and using $\dot{\eta} = \frac{1}{a}$ and Eq. (10), we obtain

$$\dot{\rho}_\Lambda = \frac{2\chi H}{a} \sqrt{\frac{3m_p^2\Omega_\Lambda}{3n^2m_p^2 + \gamma\eta^{-2}\ln(m_p^2\eta^2) + \beta\eta^{-2}},$$

(13)

where $\chi \equiv \gamma\eta^{-4} - 2\gamma\eta^{-4}\ln(m_p^2\eta^2) - 3n^2m_p^2\eta^{-2} - 2\beta\eta^{-4}$. Making use of the above Eq. (13) in (11), we obtain the following equation of state parameter of the interacting ECNADE model

$$\omega_\Lambda = -1 - \frac{2\chi}{3a} \left(\frac{\sqrt{3m_p^2\Omega_\Lambda + \gamma\eta^{-2}\ln(m_p^2\eta^2) + \beta\eta^{-2}}}{3n^2m_p^2\eta^{-2} + \gamma\eta^{-4}\ln(m_p^2\eta^2) + \beta\eta^{-4}}\right) - b^2\left(\frac{1 + \Omega_k}{\Omega_\Lambda}\right).$$

(14)

### III. CORRESPONDENCE BETWEEN ECNADE AND K-ESSENCE, TACHYON AND DILATON SCALAR FIELDS

The cosmological constant corresponds to a fluid with a constant equation of state $\omega = -1$. Now, the observations which put restriction on the value of $\omega$ to be close to that of
cosmological constant, explain bit less about time evolution of $\omega$. So we need to consider a model in which the EoS of dark energy evolves with time such as in inflationary cosmology. Scalar field models arise in string theory and are studied as promising candidates for dark energy. So far, ample literature dealing with scalar field dark energy models is available. It includes quintessence, K-essence, phantoms, tachyon, and dilaton among many. In this section, we investigate the correspondence between the interacting ECNADE model with the K-essence, tachyon and dilaton scalar fields in the non-flat FRW universe. To illustrate this correspondence, we first equate the interacting ECNADE density with the corresponding scalar field density. Then we compare the equation of state of the scalar field model with the EoS of the ECNADE.

### A. Entropy-corrected new agegraphic K-essence model

The idea of the K-essence scalar field was motivated from the Born-Infeld action of string theory and used as a source to explain the mechanism for producing the late time acceleration of the universe. The K-essence model is expressed by a general scalar field action which is function of $\phi$ and $X = \dot{\phi}^2/2$ and is given by

$$S = \int d^4x \sqrt{-g} \, p(\phi, X),$$  \hspace{1cm} (15)$$

where the Lagrangian density $p(\phi, X)$ corresponds to a pressure density as

$$p(\phi, X) = f(\phi)(-X + X^2),$$  \hspace{1cm} (16)$$

and the energy density of the field $\phi$ as

$$\rho(\phi, X) = f(\phi)(-X + 3X^2).$$  \hspace{1cm} (17)$$

The EoS parameter for the K-essence scalar field is obtained in the following way

$$\omega_K = \frac{p(\phi, X)}{\rho(\phi, X)} = \frac{X - 1}{3X - 1}. \hspace{1cm} (18)$$

After equating Eq. (18) with the ECNADE equation of state parameter (14), we determine the expression for $X$ in the form

$$X = \frac{2 + \frac{2a}{3\alpha} \sqrt{3n^2 \Omega_0 + \Omega_0 - 2} \frac{3n^2 \Omega_0 + \Omega_0 - 2}{3n^2 \Omega_0 + \Omega_0 - 2} + 3n^2 \Omega_0 + \Omega_0 - 2 + \beta \eta - \frac{4}{\sqrt{3n^2 \Omega_0 + \Omega_0 - 2} + \beta \eta}}{4 + \frac{2a}{3\alpha} \sqrt{3n^2 \Omega_0 + \Omega_0 - 2} \frac{3n^2 \Omega_0 + \Omega_0 - 2}{3n^2 \Omega_0 + \Omega_0 - 2} + 3n^2 \Omega_0 + \Omega_0 - 2 + \beta \eta - \frac{4}{\sqrt{3n^2 \Omega_0 + \Omega_0 - 2} + \beta \eta} + 3b^2 \frac{1+\Omega_0}{\Omega_0} \hspace{1cm} (19)$$
Using the above Eq. (19) and the relation $\dot{\phi}^2 = 2X$, the evolutionary form of the K-essence scalar field is determined to be

$$\dot{\phi} = \left( \frac{4 + \frac{4x}{3a} \frac{\sqrt{3m_p^2 + \frac{\gamma - 2}{\pi} \ln(m_p^2 \eta^2) + \beta \eta^{-2}}}{3a m_p^2 + \gamma - 2 + \frac{\gamma - 1}{\pi} \ln(m_p^2 \eta^2) + \beta \eta^{-2}} + 2b^2 (1 + \Omega_k) \right)^{1/2} \frac{1}{2},$$

which takes the form

$$\phi(a) - \phi(a_0) = \int_{a_0}^{a} \frac{1}{aH} \left( \frac{4 + \frac{4x}{3a} \frac{\sqrt{3m_p^2 + \frac{\gamma - 2}{\pi} \ln(m_p^2 \eta^2) + \beta \eta^{-2}}}{3a m_p^2 + \gamma - 2 + \frac{\gamma - 1}{\pi} \ln(m_p^2 \eta^2) + \beta \eta^{-2}} + 2b^2 (1 + \Omega_k) \right)^{1/2} da. \quad (21)$$

### B. Entropy-corrected new agegraphic tachyon model

In recent years, a huge interest has been devoted in studying the inflationary model with the help of tachyon field. The tachyon field associated with unstable D-branes might be responsible for cosmological inflation in the early evolution of the universe, due to tachyon condensation near the top of the effective scalar potential [23], which could suggest some new form of dark matter at late epoch [24]. A rolling tachyon has an interesting equation of state whose parameter smoothly interpolates between -1 and 0. This leads us to construct viable cosmological models by taking the tachyon as an appropriate candidate to explain inflation at high energy [25]. The effective Lagrangian density of tachyon matter is given by

$$L = -V(\phi) \sqrt{1 + \partial_\mu \phi \partial^\mu \phi},$$

where $V(\phi)$ is the tachyon potential. The energy density and pressure for the tachyon are written to be

$$\rho_T = \frac{V(\phi)}{\sqrt{1 - \dot{\phi}^2}}, \quad (23)$$

$$p_T = -V(\phi) \sqrt{1 - \dot{\phi}^2},$$

where $V(\phi)$ represents the tachyon potential. While the equation of state of the tachyon is given by

$$\omega_T = \frac{p_T}{\rho_T} = \dot{\phi}^2 - 1. \quad (25)$$
In order to develop the correspondence between the ECNADE and tachyon dark energy, we compare Eqs.(25) and (14), and obtain

\[ \dot{\phi}^2 = -\frac{2\chi}{3a} \frac{\sqrt{\frac{3n^2m_p^2\Omega_k}{3n^2m_p^2\eta^{-2} + \gamma\eta^{-4} \ln(m_p^2\eta^2) + \beta\eta^{-2}}} - b^2\left(1 + \frac{\Omega_k}{\Omega_\Lambda}\right)}{3n^2m_p^2\eta^{-2} + \gamma\eta^{-4} \ln(m_p^2\eta^2) + \beta\eta^{-4}} \]  

(26)

Now equating the Eqs. (23) and (9), we get the following expression of potential energy for the tachyon

\[ V(\phi) = (3n^2m_p^2\eta^{-2} + \gamma\eta^{-4} \ln(m_p^2\eta^2) + \beta\eta^{-4}) \times \left(1 + \frac{2\chi}{3a} \frac{\sqrt{\frac{3n^2m_p^2\Omega_k}{3n^2m_p^2\eta^{-2} + \gamma\eta^{-4} \ln(m_p^2\eta^2) + \beta\eta^{-2}}} + b^2\left(1 + \frac{\Omega_k}{\Omega_\Lambda}\right)^{1/2}\right). \]  

(27)

We obtain the evolutionary form of the tachyon scalar field

\[ \phi(a) - \phi(a_0) = \int_{a_0}^{a} \frac{1}{aH} \left(-\frac{2\chi}{3a} \sqrt{\frac{3n^2m_p^2\Omega_k}{3n^2m_p^2\eta^{-2} + \gamma\eta^{-4} \ln(m_p^2\eta^2) + \beta\eta^{-2}}} - b^2\left(1 + \frac{\Omega_k}{\Omega_\Lambda}\right)^{1/2}\right) \, da. \]  

(28)

C. Entropy-corrected new agegraphic dilaton model

A dilaton scalar field which exhibits the features of dark energy is usually originated from the lower-energy limit of string theory. This model is explained by a general four-dimensional effective low-energy string action. It has been shown that a scalar field possessing negative kinetic term (usually known as phantom type scalar field) does not necessarily lead to inconsistencies provided that one takes an appropriate structure of higher order kinetic terms in the effective (underlying) theory. The pressure density and the energy density of the dilaton dark energy model is given by

\[ p_D = -X + ce^{\lambda\phi}X^2, \]  

(29)

\[ \rho_D = -X + 3ce^{\lambda\phi}X^2, \]  

(30)

where \( c \) and \( \lambda \) are positive constants and \( \dot{\phi}^2 = 2X \). The EoS parameter for the dilaton scalar field is given by

\[ \omega_D = \frac{p_D}{\rho_D} = \frac{-1 + ce^{\lambda\phi}X}{-1 + 3ce^{\lambda\phi}X}. \]  

(31)
Following the same steps as done for the above cases, the comparison of Eq. (31) with (14), yields

\[ ce^{\lambda \phi} X = \frac{2 + 2 \chi}{3a} \left[ \frac{3m_B^2 \Omega_A}{3m^2 + \gamma \eta^{-2} \ln(m_\Lambda^2 \eta^2) + \beta \eta^{-2}} \right] + b^2 \left( \frac{1+\Omega_k}{\Omega_A} \right). \]  \tag{32}

Insert the value of \( X = \phi^2/2 \) in the above equation (32), we get

\[ ce^{\lambda \phi} \phi^2 = \frac{4 + 4 \chi}{3a} \left[ \frac{3m_B^2 \Omega_A}{3m^2 + \gamma \eta^{-2} \ln(m_\Lambda^2 \eta^2) + \beta \eta^{-2}} \right] + 2b^2 \left( \frac{1+\Omega_k}{\Omega_A} \right). \]  \tag{33}

The above equation can be written as

\[ e^{\frac{\lambda \phi}{2}} = \left( \frac{4 + 4 \chi}{3a} \left[ \frac{3m_B^2 \Omega_A}{3m^2 + \gamma \eta^{-2} \ln(m_\Lambda^2 \eta^2) + \beta \eta^{-2}} \right] + 2b^2 \left( \frac{1+\Omega_k}{\Omega_A} \right) \right)^{1/2}, \]  \tag{34}

and its integration yields

\[ \phi(a) = \frac{2}{\bar{\lambda}} \ln \left[ e^{\frac{\lambda \phi(a_0)}{2}} + \frac{\lambda}{2 \sqrt{c}} \int_{a_0}^{a} \frac{1}{aH} \left( 4 + 4 \chi \left[ \frac{3m_B^2 \Omega_A}{3m^2 + \gamma \eta^{-2} \ln(m_\Lambda^2 \eta^2) + \beta \eta^{-2}} \right] + 2b^2 \left( \frac{1+\Omega_k}{\Omega_A} \right) \right)^{1/2} da \right]. \]  \tag{35}

In summary, in this manuscript we have discussed the new agegraphic dark energy model from the inclusion of quantum correction in the entropy-area relation. This ECNADE interacts with cold dark matter in the FRW spacetime. We have established a correspondence between ECNADE density with different scalar fields namely, tachyon, K-essence and dilaton scalar field in the non-flat FRW universe. We have reconstructed the potentials and the kinetic energies corresponding to each model which describe tachyon, K-essence and dilaton cosmology.

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