Thermodynamical description of the interacting new agegraphic dark energy

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We describe the thermodynamical interpretation of the interaction between new agegraphic dark energy and dark matter in a non-flat universe. When new agegraphic dark energy and dark matter evolve separately, each of them remains in thermodynamic equilibrium. As soon as an interaction between them is taken into account, their thermodynamical interpretation changes by a stable thermal fluctuation. We obtain a relation between the interaction term of the dark components and this thermal fluctuation.

Keywords: dark energy; thermodynamics; entropy.

I. INTRODUCTION

The dark energy puzzle is one of the biggest challenges of the modern cosmology in the past decade. There is an ample evidences on the observational side that our universe is currently experiencing a phase of accelerated expansion $^{[1–4]}$. These observations suggest that nearly three quarters of our universe consists of a mysterious energy component (dark energy) which is responsible for this expansion, and the remaining part consists of pressureless dark matter. Nevertheless, despite the mounting observational evidences, the nature of such dark energy remains elusive and it has become a source of much debate except for the fact that it has negative pressure. Most discussions on dark energy rely on the assumption that it evolves independently of dark matter. Given the unknown nature of both dark energy and dark matter 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. Indeed, this possibility has received a lot of attention recently (see $^{[5–20]}$ and references therein). In particular, it has been shown that the coupling can alleviate the coincidence problem $^{[21]}$. Furthermore, it was argued that the appropriate coupling between dark components can influence the perturbation dynamics and the cosmic microwave background (CMB) spectrum and account for the observed CMB low l suppression $^{[22]}$. It was shown that

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in a model with interaction the structure formation has a different fate as compared with the non-interacting case [22]. It was also discussed that with strong coupling between dark energy and dark matter, the matter density perturbation is stronger during the universe evolution till today, which shows that the interaction between dark energy and dark matter enhances the clustering of dark matter perturbation compared to the noninteracting case in the past. Therefore, the coupling between dark components could be a major issue to be confronted in studying the physics of dark energy. However, so long as the nature of these two components remain unknown it will not be possible to derive the precise form of the interaction from first principles. Therefore, one has to assume a specific coupling from the outset [23–25] or determine it from phenomenological requirements [26, 27]. Thermodynamical description of the interaction (coupling) between holographic dark energy and dark matter has been studied in [28, 29].

Among the various candidates to explain the accelerated expansion, the agegraphic and new agegraphic dark energy (NADE) models condensate in a class of quantum gravity may have interesting cosmological consequences. These models take into account the Heisenberg uncertainty relation of quantum mechanics together with the gravitational effect in general relativity. The agegraphic dark energy models assume that the observed dark energy comes from the spacetime and matter field fluctuations in the universe [30–32]. 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 [33–46]. 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.

The main purpose of this Letter is to study thermodynamical interpretation of the interaction between dark matter and NADE model for a universe enveloped by the apparent horizon. It was shown that for an accelerating universe the apparent horizon is a physical boundary from the thermodynamical point of view [47]. In particular, it was argued that for an accelerating universe inside the event horizon the generalized second law does not satisfy, while the accelerating universe
enveloped by the apparent horizon satisfies the generalized second law of thermodynamics\textsuperscript{47–50}. Therefore, the event horizon in an accelerating universe might not be a physical boundary from the thermodynamical point of view. This Letter is outlined as follows. In the next section we consider the thermodynamical picture of the non-interacting NADE in a non-flat universe. In section III we extend the thermodynamical description in the case where there is an interaction term between the dark components. We also present an expression for the interaction term in terms of a thermal fluctuation. The last section is devoted to summary and discussion.

II. THERMODYNAMICAL DESCRIPTION OF THE NON-INTERACTING NADE

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

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

(1)

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\textsuperscript{51–54}. The first Friedmann equation takes the form

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

(2)

where $H = \dot{a}/a$ is the Hubble parameter, $\rho_m$ and $\rho_D$ are the energy density of dark matter and dark energy, respectively. We define, as usual, the fractional energy densities such as

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

Thus, the Friedmann equation can be written

$$\Omega_m + \Omega_D = 1 + \Omega_k. \quad (4)$$

Let us first review the origin of the agegraphic dark energy model. Following the line of quantum fluctuations of spacetime, Karolyhazy et al.\textsuperscript{55–57} 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, Sasakura discussed that the energy density of metric fluctuations of the Minkowski spacetime is given by\textsuperscript{58} (see also\textsuperscript{59, 60})

$$\rho_D \sim \frac{1}{t_p^2 t^2} \sim \frac{m_p^2}{t^2}, \quad (5)$$
where $t_p$ is the reduced Planck time and $t$ is a proper time scale. On these basis, Cai wrote down the energy density of the original agegraphic dark energy as

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

(6)

where $T_A$ is the age of the universe,

$$T_A = \int_{a_0}^{a} \frac{da}{Ha},$$

(7)

and 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. However, to avoid some internal inconsistencies in the original agegraphic dark energy 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 [31]. The NADE 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 NADE resolved this issue [31]. The energy density of the NADE can be written

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

(8)

where the conformal time $\eta$ is given by

$$\eta = \int \frac{dt}{a} = \int_{a_0}^{a} \frac{da}{Ha^2}.$$
Here the prime stands for the derivative with respect to $x = \ln a$. Taking the derivative with respect to the cosmic time of Eq. (8) and using Eq. (12) we get

$$\dot{\rho}_D = -2H\sqrt{\Omega_D^0}n\rho_D. \tag{14}$$

Inserting this relation into Eq. (10) we obtain the equation of state parameter of the NADE

$$1 + w^0_D = \frac{2}{3na}\sqrt{\Omega_D^0}. \tag{15}$$

We also limit ourselves to the assumption that the thermal system bounded by the apparent horizon remains in equilibrium so that the temperature of the system must be uniform and the same as the temperature of its boundary. This requires that the temperature $T$ of the energy content inside the apparent horizon should be in equilibrium with the temperature $T_h$ associated with the apparent horizon, so we have $T = T_h$. This expression holds in the local equilibrium hypothesis. If the temperature of the fluid differs much from that of the horizon, there will be spontaneous heat flow between the horizon and the fluid and the local equilibrium hypothesis will no longer hold. This is also at variance with the FRW geometry. Thus, when we consider the thermal equilibrium state of the universe, the temperature of the universe is associated with the horizon temperature. In this picture the equilibrium entropy of the NADE is connected with its energy and pressure through the first law of thermodynamics

$$TdS_D = dE_D + p_DdV, \tag{16}$$

where the volume enveloped by the apparent horizon is given by

$$V = \frac{4\pi}{3}r^3_A, \tag{17}$$

and $r_A$ is the apparent horizon radius. The apparent horizon was argued as a causal horizon for a dynamical spacetime and is associated with gravitational entropy and surface gravity [61–63]. For the FRW universe the apparent horizon radius reads [64, 65]

$$r_A = \frac{1}{\sqrt{H^2 + k/a^2}}. \tag{18}$$

The total energy of the NADE inside the apparent horizon is

$$E_D = \rho_DV = \frac{4\pi n^2m^2_Ar^3_A}{\eta^2}. \tag{19}$$

Taking the differential form of Eq. (19) and using Eq. (12), we find

$$dE_D = 4\pi m^2_\eta(r^0_A)^2H^2_0\Omega_D^0 \left[3dr^0_A - 2r^0_AH_0\sqrt{\Omega_D^0}\right]. \tag{20}$$
The associated temperature on the apparent horizon can be written as

\[ T = \frac{1}{2\pi r_A}. \]  

(21)

Inserting Eqs. (17), (20) and (21) into (16), we obtain

\[ dS_D^{(0)} = 8\pi^2 m_p^2 (r_A^0)^3 H_0^2 \Omega_D^0 \left[ 3(1 + w_D^0)dr_A^0 - 2\frac{r_A^0}{n} H_0 \sqrt{\Omega_D^0} d\eta^0 \right], \]  

(22)

Using Eq. (15) as well as relation \( H_0 d\eta^0 = dx^0/a_0 \), we find

\[ dS_D^{(0)} = 16\pi^2 m_p^2 (r_A^0)^3 H_0^2 \Omega_D^0 \sqrt{\Omega_D^0} na_0 \left[ dr_A^0 - r_A^0 dx^0 \right]. \]  

(23)

Here the superscript/subscript \((0)\) denotes that in this picture our universe is in a thermodynamical stable equilibrium.

### III. THERMODYNAMICAL DESCRIPTION OF THE INTERACTING NADE

In this section we study the case where the pressureless dark matter and the NADE interact with each other. In this case \( \rho_m \) and \( \rho_D \) do not conserve separately; they must rather enter the energy balances

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

(24)

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

(25)

Here \( Q \) denotes the interaction term and can be taken as \( Q = 3b^2 H (\rho_m + \rho_D) \) with \( b^2 \) being a coupling constant \[21\]. Inserting Eq. (14) into (25), we obtain the equation of state parameter of the interacting NADE

\[ 1 + w_D = \frac{2}{3n} \sqrt{\Omega_D} - \frac{Q}{9m_p^2 H^3 \Omega_D}. \]  

(26)

The evolution behavior of the NADE is now given by \[40\]

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

(27)

Comparing Eq. (26) with Eq. (15), we see that the presence of the interaction term \( Q \) has provoked a change in the equation of state parameter and consequently in the dimensionless density parameter of the dark energy component and thus now there is no subscript above the aforesaid quantities to denote the absence of interaction. The interacting NADE model in the non-flat
universe as described above is not anymore thermodynamically interpreted as a state in thermodynamical equilibrium. Indeed, as soon as an interaction between dark components is taken into account, they cannot remain in their respective equilibrium states. The effect of interaction between the dark components is thermodynamically interpreted as a small fluctuation around the thermal equilibrium. It was shown \[66\] that due to the fluctuation, there is a leading logarithmic correction \( S^{(1)}_D = -\frac{1}{2} \ln(CT^2) \) to the thermodynamic entropy around equilibrium in all thermodynamical systems. Therefore, the entropy of the NADE is connected with its energy and pressure through the first law of thermodynamics

\[
TdS_D = dE_D + p_D dV,
\]

where now the entropy has been assigned an extra logarithmic correction \[66\]

\[
S_D = S^{(0)}_D + S^{(1)}_D,
\]

where the leading logarithmic correction is

\[
S^{(1)}_D = -\frac{1}{2} \ln(CT^2),
\]

and \( C \) is the heat capacity defined by

\[
C = T \frac{\partial S^{(0)}_D}{\partial T}.
\]

It is a matter of calculation to show that

\[
C = -16\pi^2 m_p^2 (r_A^0)^4 H_0^2 \omega_D^0 \sqrt{\omega_D^0 n a_0},
\]

and therefore

\[
S^{(1)}_D = -\frac{1}{2} \ln \left( -4m_p^2 (r_A^0)^2 H_0^2 \omega_D^0 \sqrt{\omega_D^0 n a_0} \right).
\]

Substituting the expressions for the volume, energy, and temperature in Eq. \(28\) for the interacting case, we get

\[
dS_D = 8\pi^2 m_p^2 r_A^3 H^2 \omega_D \left[ 3(1 + w_D) dr_A - \frac{2r_A}{n} H \sqrt{\omega_D} d\eta \right],
\]

or in another way

\[
dS_D = 8\pi^2 m_p^2 r_A^3 H^2 \omega_D \left[ 3(1 + w_D) dr_A - \frac{2r_A}{na} \sqrt{\omega_D} dx \right],
\]
and thus one gets
\[
1 + w_D = \frac{1}{24\pi^2 m_p^2 r_A^3 H^2 \Omega_D} \frac{dS_D}{dr_A} + \frac{2r_A}{3na} \sqrt{\Omega_D} \frac{dx}{dr_A},
\]

\[
= \frac{1}{24\pi^2 m_p^2 r_A^3 H^2 \Omega_D} \left[ \frac{dS_D^{(0)}}{dr_A} + \frac{dS_D^{(1)}}{dr_A} \right] + \frac{2r_A}{3na} \sqrt{\Omega_D} \frac{dx}{dr_A}.
\]

Employing Eqs. (23), (30)-(33), we can easily find
\[
\frac{dS_D^{(0)}}{dr_A} = \frac{\partial S_D^{(0)}}{\partial r_A} \frac{dr_A}{dr_A} + \frac{\partial S_D^{(0)}}{\partial x} \frac{dx}{dr_A} = 16\pi^2 m_p^2 (r_A^0)^3 H_0^2 (\Omega_D^0)^{3/2} \left( \frac{dr_A^0}{dr_A} - (r_A^0 \frac{dx}{dr_A}) \right),
\]

\[
\frac{dS_D^{(1)}}{dr_A} = \frac{\partial S_D^{(1)}}{\partial r_A} \frac{dr_A}{dr_A} = \frac{1}{r_A} \frac{dr_A}{dr_A}.
\]

Finally, by equating expressions (26) and (36) for the equation of state parameter of the interacting NADE evaluated on cosmological and thermodynamical sides, respectively, one gets an expression for the interaction term
\[
\frac{Q}{9m_p^2 H^3} = \frac{2\sqrt{\Omega_D}}{3na} \Omega_D \left( 1 - r_A \frac{dx}{dr_A} \right) - \frac{1}{24\pi^2 m_p^2 r_A^3 H^2} \left[ \frac{dS_D^{(0)}}{dr_A} + \frac{dS_D^{(1)}}{dr_A} \right]
\]

\[
= \frac{2\sqrt{\Omega_D}}{3na} \Omega_D \left( 1 - r_A \frac{dx}{dr_A} \right) + \frac{H_0^2 (\Omega_D^0)^{3/2}}{3na} \left( \frac{r_A^0}{r_A} \right)^3 \left( \frac{dr_A^0}{dr_A} - (r_A^0 \frac{dx}{dr_A}) \right)
\]

\[
+ \frac{1}{24\pi^2 m_p^2 r_A^3 H^2 \Omega_D} \frac{dr_A}{dr_A}.
\]

In this way we provide the relation between the interaction term of the dark components and the thermal fluctuation.

IV. SUMMARY AND DISCUSSION

One of the important questions concerns the thermodynamical behavior of the accelerated expanding universe driven by dark energy. It is interesting to ask whether thermodynamics in an accelerating universe can reveal some properties of dark energy. It was first pointed out in [67] that the hyperbolic second order partial differential Einstein equation has a predisposition to the first law of thermodynamics. The profound connection between the thermodynamics and the gravitational field equations has also been observed in the cosmological situations [68–75]. This connection implies that the thermodynamical properties can help understand the dark energy, which gives strong motivation to study thermodynamics in the accelerating universe.

Although at this point the interaction between dark energy and dark matter looks purely phenomenological, but in the absence of a symmetry that forbids the interaction there is nothing, in
principle, against it. Further, the interacting dark materdark energy (the latter in the form of a quintessence scalar field and the former as fermions whose mass depends on the scalar field) has been investigated at one quantum loop with the result that the coupling leaves the dark energy potential stable if the former is of exponential type but it renders it unstable otherwise. Thus, microphysics seems to allow enough room for the coupling; however, this point is not fully settled and should be further investigated. Recently evidence was provided by the Abell Cluster A586 in support of the interaction between dark energy and dark matter [76, 77].

In this Letter, we provided a thermodynamical description for the NADE model in a universe with spacial curvature. It was shown that for an accelerating universe the apparent horizon is a physical boundary from the thermodynamical point of view. We explored the thermodynamical picture of the interacting NADE model for a FRW universe enveloped by the apparent horizon. The NADE 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 NADE resolved this issue. We assumed that in the absence of a coupling, the two dark components remain in separate thermal equilibrium and that the presence of a small coupling between them can be described as stable fluctuations around equilibrium. Finally, resorting to the logarithmic correction to the equilibrium entropy we derived an expression for the interaction term in terms of a thermal fluctuation.

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