The generalized second law for the interacting new agegraphic dark energy in a non-flat FRW universe enclosed by the apparent horizon

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Abstract

We investigate the validity of the generalized second law of gravitational thermodynamics in a non-flat FRW universe containing the interacting new agegraphic dark energy with cold dark matter. The boundary of the universe is assumed to be enclosed by the dynamical apparent horizon. We show that for this model, the equation of state parameter can cross the phantom divide. We also present that for the selected model under thermal equilibrium with the Hawking radiation, the generalized second law is always satisfied throughout the history of the universe. Whereas, the evolution of the entropy of the universe and apparent horizon, separately, depends on the equation of state parameter of the interacting new agegraphic dark energy model.

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1 Introduction

Type Ia supernovae observational data suggest that the universe is dominated by two dark components containing dark matter and dark energy [1]. Dark matter (DM), a matter without pressure, is mainly used to explain galactic curves and large-scale structure formation, while dark energy (DE), an exotic energy with negative pressure, is used to explain the present cosmic accelerating expansion. However, the nature of DE is still unknown, and people have proposed some candidates to describe it. The cosmological constant, $\Lambda$, is the most obvious theoretical candidate of DE, which has the equation of state $\omega = -1$. Astronomical observations indicate that the cosmological constant is many orders of magnitude smaller than estimated in modern theories of elementary particles [2]. Also the "fine-tuning" and the "cosmic coincidence" problems are the two well-known difficulties of the cosmological constant problems [3].

There are different alternative theories for the dynamical DE scenario which have been proposed by people to interpret the accelerating universe. i) The scalar-field models of DE including quintessence [4], phantom (ghost) field [5], K-essence [6] based on earlier work of K-inflation [7], tachyon field [8], dilatonic ghost condensate [9], quintom [10], and so forth. ii) The interacting DE models including Chaplygin gas [11], holographic DE models [12], and braneworld models [13], etc. The interaction between DE and DM has been discussed in ample detail by [14]. The recent evidence provided by the Abell Cluster A586 supports the interaction between DE and DM [15]. However, there are no strong observational bounds on the strength of this interaction [16].

Recently, the original agegraphic dark energy (ADE) and the new agegraphic dark energy (NADE) models were proposed by Cai [17] and Wei & Cai [18], respectively. The original ADE model cannot explain the matter-dominated era [17]. Thus, Wei and Cai [18] proposed the NADE, while the age of the universe has been replaced by the conformal time scale. The evolution behavior of the NADE is very different from that of original ADE. Instead the evolution behavior of the NADE is similar to that of the holographic DE [12]. But some essential differences exist between them. In particular, the NADE model is free of the drawback concerning causality problem which exists in the holographic DE model. The ADE and NADE models have been studied in ample detail by [19, 20, 21, 22].

Besides, as usually believed, an early inflation era leads to a flat universe. This is not a necessary consequence if the number of e-foldings is not very large [23]. It is still possible that there is a contribution to the Friedmann equation from the spatial curvature when studying the late universe, though much smaller than other energy components according to observations. Therefore, it is not just of academic interest to study a universe with a spatial curvature marginally allowed by the inflation model as well as observations. Some experimental data have implied that our universe is not a perfectly flat universe and that it possesses a small positive curvature [24].

In the semiclassical quantum description of black hole physics, it was found that black holes emit Hawking radiation with a temperature proportional to their surface gravity at the event horizon and they have an entropy which is one quarter of the area of the event horizon in Planck unit [25]. The temperature, entropy and mass of black holes satisfy the first law of thermodynamics [26]. On the other hand, it was shown that the Einstein equation can be derived from the first law of thermodynamics by assuming the proportionality of entropy and the horizon area [27]. The study on the relation between the Einstein equation and the first law of thermodynamics has been generalized to the cosmological context where it was shown that the first law of thermodynamics on the apparent horizon $r_A$ can be derived from the Friedmann equation and vice versa if we take the Hawking temperature $T_A = 1/2\pi r_A$ and the entropy
\[ S_{A} = \pi \tilde{r}_{A}^{2} \] on the apparent horizon [28]. Furthermore, the equivalence between the first law of thermodynamics and Friedmann equation was also found for gravity with Gauss-Bonnet term and the Lovelock gravity theory [28, 29].

Besides the first law of thermodynamics, a lot of attention has been paid to the generalized second law of thermodynamics in the accelerating universe driven by DE. The generalized second law of thermodynamics is as important as the first law, governing the development of the nature [30, 31, 32, 33, 34, 35]. Note that in [35], the authors investigated the validity of the first and the generalized second law of thermodynamics for both apparent and event horizon for the case of interacting holographic DE with DM. They showed that in contrast to the case of the apparent horizon, both the first and second law of thermodynamics breakdown if one consider the universe to be enveloped by the event horizon with the usual definitions of entropy and temperature. They argued that the break down of the first law can be attributed to the possibility that the first law may only apply to variations between nearby states of local thermodynamic equilibrium, while the event horizon reflects the global spacetime properties. Besides in the dynamic spacetime, the horizon thermodynamics is not as simple as that of the static spacetime. The event horizon and apparent horizon are in general different surfaces. The definition of thermodynamical quantities on the cosmological event horizon in the nonstatic universe are probably ill-defined. Author of [36] by redefining the event horizon measured from the sphere of the horizon as the system’s IR cut-off for an interacting holographic DE model in a non-flat universe, showed that the second law is satisfied for the special range of the deceleration parameter. Recently, Sheykhi [37] showed that both the first and generalized second law of thermodynamics are respected for the non-flat universe enveloped by the apparent horizon in braneworld scenarios.

All mentioned in above motivate us to investigate the generalized second law of thermodynamics for the interacting NADE model with DM in the non-flat universe enclosed by the apparent horizon with the Hawking radiation. To do this, in Section 2, we study the NADE model in a non-flat universe which is in interaction with the cold DM. In Section 3, we investigate the validity of the generalized second law of thermodynamics for the present model enclosed by the apparent horizon which is in thermal equilibrium with the Hawking radiation. Section 4 is devoted to conclusions.

## 2 Interacting NADE model and DM

We consider the Friedmann-Robertson-Walker (FRW) metric for the non-flat universe as

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

where \( k = 0, 1, -1 \) represent a flat, closed and open FRW universe, respectively. Observational evidences support the existence of a closed universe with a small positive curvature (\( \Omega_k \sim 0.02 \)) [24]. Define \( \tilde{r} = ar \), the metric (1) can be rewritten as \( ds^2 = h_{ab}dx^a dx^b + \tilde{r}^2d\Omega^2 \), where \( x^a = (t, r) \), \( h_{ab} = \text{diag}(-1, a^2/(1 - kr^2)) \). By definition, \( h^{ab}\partial_a\tilde{r}\partial_b\tilde{r} = 0 \), the location of the apparent horizon in the FRW universe is obtained as \( \tilde{r} = r_A = (H^2 + k/a^2)^{-1/2} \) [38]. For \( k = 0 \), the apparent horizon is same as the Hubble horizon.

The first Friedmann equation for the non-flat FRW universe has the following form

\[ H^2 + \frac{k}{a^2} = \frac{8\pi}{3} (\rho_\Lambda + \rho_m), \tag{2} \]

where we take \( G = 1 \). Also \( \rho_\Lambda \) and \( \rho_m \) are the energy density of DE and DM, respectively. Let
us define the dimensionless energy densities as
\[ \Omega_m = \frac{\rho_m}{\rho_{cr}} = \frac{8\pi \rho_m}{3H^2}, \quad \Omega_\Lambda = \frac{\rho_\Lambda}{\rho_{cr}} = \frac{8\pi \rho_\Lambda}{3H^2}, \quad \Omega_k = \frac{k}{a^2H^2}, \] (3)
then, the first Friedmann equation yields
\[ \Omega_m + \Omega_\Lambda = 1 + \Omega_k. \] (4)
Following [21], the energy density of the NADE is given by
\[ \rho_\Lambda = \frac{3n^2}{8\pi \eta^2}, \] (5)
where \( n \) is a constant. The astronomical data gives \( n = 2.716^{+0.111}_{-0.109} \) [22]. Also \( \eta \) is conformal time of the FRW universe, and given by
\[ \eta = \int \frac{dt}{a} = \int_0^a \frac{da}{Ha^2}. \] (6)
The DE density (5) is similar to that of the holographic DE [12], but the conformal time stands instead of the future event horizon distance of the universe. This solves the causality problem which exists in the holographic DE model. Because the existence of the future event horizon requires an eternal accelerated expansion of the universe [18].
From definition \( \rho_\Lambda = 3H^2\Omega_\Lambda/8\pi \), we get
\[ \eta = \frac{n}{H\sqrt{\Omega_\Lambda}}. \] (7)
We consider a universe containing an interacting NADE density \( \rho_\Lambda \) and the cold dark matter (CDM), with \( \omega_m = 0 \). The energy equations for NADE and CDM are given by
\[ \dot{\rho}_\Lambda + 3H(1 + \omega_\Lambda)\rho_\Lambda = -Q, \] (8)
\[ \dot{\rho}_m + 3H\rho_m = Q, \] (9)
where following [39], we choose \( Q = \Gamma \rho_\Lambda \) as an interaction term and \( \Gamma = 3b^2H(\frac{1+\Omega_k}{\Omega_\Lambda}) \) is the decay rate of the NADE component into CDM with a coupling constant \( b^2 \). The choice of the interaction between both components was to get a scaling solution to the coincidence problem such that the universe approaches a stationary stage in which the ratio of DE and DM becomes a constant [40]. The dynamics of interacting DE models with different \( Q \)-classes have been studied in ample detail by [41]. The freedom of choosing the specific form of the interaction term \( Q \) stems from our incognizance of the origin and nature of DE as well as DM. Moreover, a microphysical model describing the interaction between the dark components of the universe is not available nowadays [42].
Taking the time derivative of Eq. (5), using \( \dot{\eta} = 1/a \) and Eq. (7) yields
\[ \dot{\rho}_\Lambda = -\frac{2H\sqrt{\Omega_\Lambda}}{na} \rho_\Lambda. \] (10)
Substituting Eq. (10) in (8), gives the equation of state (EoS) parameter as
\[ \omega_\Lambda = -1 + \frac{2\sqrt{\Omega_\Lambda}}{3na} - b^2\left(\frac{1 + \Omega_k}{\Omega_\Lambda}\right), \] (11)
which shows that for $b^2 = 0$ then $\omega_\Lambda > -1$ and cannot behaves phantom EoS. However, in the presence of interaction, $b^2 \neq 0$, taking $\Omega_\Lambda = 0.72$, $\Omega_k = 0.02$ [24], $n = 2.7$ [22] and $a = 1$ for the present time, Eq. (11) gives
\[ \omega_\Lambda = -0.79 - 1.42b^2, \] (12)
which clears that the phantom EoS $\omega_\Lambda < -1$ can be obtained when $b^2 > 0.15$ for the interaction between NADE and CDM.

The deceleration parameter is given by
\[ q = -\left(1 + \frac{\dot{H}}{H^2}\right). \] (13)
Taking the time derivative in both sides of Eq. (2), and using Eqs. (3), (4), (8) and (9), we get
\[ q = -\frac{3}{2} \Omega_\Lambda + \frac{\Omega_\Lambda^{3/2}}{na} + \frac{1}{2}(1 - 3b^2)(1 + \Omega_k). \] (14)
Now taking $\Omega_\Lambda = 0.72$, $\Omega_k = 0.02$ [24], $n = 2.7$ [22] and $a = 1$ for the present time we get
\[ q = -0.34 - 1.53b^2, \] (15)
which is always negative even in the absence of interaction between NADE and CDM. Therefore the NADE model in the present time can drive the universe to accelerated expansion.

### 3 Generalized second law of thermodynamics

Here, we study the validity of the generalized second law (GSL) of gravitational thermodynamics. According to the GSL, entropy of the NADE and CDM inside the horizon plus the entropy of the horizon do not decrease with time [35]. In the GSL, the definition of the temperature of the fluid is important. Cai & Kim [28] proofed that the Friedmann equations in Einstein gravity are derived by applying the first law of thermodynamics to the dynamic apparent horizon, $\tilde{r}_A = (H^2 + k/a^2)^{-1/2}$, of a FRW universe with any spatial curvature in arbitrary dimensions and assuming that the apparent horizon has an associated entropy $S_A$ and Hawking temperature $T_A$ as $S_A = \pi \tilde{r}_A^2$, $T_A = 1/2\pi \tilde{r}_A$. In the braneworld scenarios, the Friedmann equations also can be written directly in the form of the first law of thermodynamics, at the apparent horizon with the Hawking temperature on the brane, regardless of whether there is the intrinsic curvature term on the brane or a Gauss-Bonnet term in the bulk [37]. Recently the Hawking radiation with temperature $T_A = 1/2\pi \tilde{r}_A$ on the apparent horizon of a FRW universe with any spatial curvature has been observed in [38] which gives more solid physical implication of the temperature associated with the apparent horizon. The Hawking temperature is measured by an observer with the Kodoma vector inside the apparent horizon [38]. These motivate us to consider the Hawking temperature of the dynamic apparent horizon for our model. We also limit ourselves to the assumption that the thermal system including the NADE and CDM bounded by the apparent horizon remain 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 both NADE and CDM inside the apparent horizon should be in equilibrium with the Hawking temperature $T_A$ associated with the apparent horizon, so we have $T = T_A$. This expression holds in the local equilibrium hypothesis. If the temperature of the system 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 [32, 33].
The entropy of the universe including the DE and CDM inside the apparent horizon can be related to its energy and pressure in the horizon by Gibb’s equation \([32, 33, 35]\)

\[
T dS = dE + P dV,
\]

(16)

where like \([35]\), \(V = 4\pi \tilde{r}_A^3 / 3\) is the volume containing the NADE and CDM with the radius of the apparent horizon \(\tilde{r}_A\) and \(T = T_A = 1 / (2\pi \tilde{r}_A)\) is the Hawking temperature of the apparent horizon. Also

\[
E = \frac{4\pi \tilde{r}_A^3}{3} (\rho_{\Lambda} + \rho_m),
\]

(17)

\[
P = P_{\Lambda} + P_m = P_{\Lambda} = \omega_{\Lambda} \rho_{\Lambda} = \frac{3H^2}{8\pi} \omega_{\Lambda} \Omega_{\Lambda}.
\]

(18)

For the dynamical apparent horizon

\[
\tilde{r}_A = H^{-1} (1 + \Omega_k)^{-1/2},
\]

(19)

its derivative with respect to cosmic time \(t\) yields

\[
\dot{\tilde{r}}_A = \frac{3(1 + \Omega_k + \Omega_{\Lambda} \omega_{\Lambda})}{2(1 + \Omega_k)^{3/2}}.
\]

(20)

Taking the derivative in both sides of (16) with respect to cosmic time \(t\), and using Eqs. (2), (3), (4), (8), (9), (17), (18), (19), and (20), we obtain the evolution of the entropy in the universe containing the NADE and CDM as

\[
\dot{S} = \frac{3\pi}{2H(1 + \Omega_k)^{3/2}} [1 + \Omega_k + 3\Omega_{\Lambda} \omega_{\Lambda}] (1 + \Omega_k + \Omega_{\Lambda} \omega_{\Lambda}).
\]

(21)

Equation (21) shows that for

\[
\omega_{\Lambda} \leq -\left(\frac{1 + \Omega_k}{\Omega_{\Lambda}}\right), \quad \omega_{\Lambda} \geq -\frac{1}{3} \left(\frac{1 + \Omega_k}{\Omega_{\Lambda}}\right),
\]

(22)

the contribution of the entropy of the universe inside the dynamical apparent horizon in the GSL is positive, i.e. \(\dot{S} \geq 0\). Taking \(\Omega_{\Lambda} = 0.72\), \(\Omega_k = 0.02\) \([24]\) for the present time and using Eq. (12), conditions (22) reduce to \(b^2 \geq 0.44\).

Also in addition to the entropy in the universe, there is a geometric entropy on the apparent horizon \(S_A = \pi \tilde{r}_A^2\) \([35]\). The evolution of this horizon entropy is obtained as

\[
\dot{S}_A = \frac{3\pi}{H(1 + \Omega_k)^2} (1 + \Omega_k + \Omega_{\Lambda} \omega_{\Lambda}).
\]

(23)

Equation (23) clears that for

\[
\omega_{\Lambda} \geq -\left(\frac{1 + \Omega_k}{\Omega_{\Lambda}}\right),
\]

(24)

the contribution of the dynamical apparent horizon in the GSL is positive, i.e. \(\dot{S}_A \geq 0\). Taking the above-mentioned values for the fractional densities for the present time and using Eq. (12) again, condition (24) yields \(b^2 \leq 0.44\). Therefore for a given coupling constant of interaction \(b^2\) at the present time, entropy of the universe and apparent horizon can not be an increasing function of time, simultaneously.
Finally, using Eqs. (21) and (23), the GSL due to different contributions of the NADE, CDM and apparent horizon can be obtained as
\[
\dot{S}_{\text{tot}} = \frac{9\pi}{2H(1+\Omega_k)^3}(1+\Omega_k + \Omega_\Lambda \omega_\Lambda)^2 \geq 0,
\] (25)
where \(S_{\text{tot}} = S + S_A\) is the total entropy. Equation (25) presents that the GSL for the universe containing the interacting NADE with CDM enclosed by the dynamical apparent horizon is always satisfied throughout the history of the universe for any spatial curvature and it is independent of the EoS parameter of the interacting NADE model.

4 Conclusions

Here we considered the NADE model, in the presence of interaction between DE and DM, for the universe with spatial curvature. We obtained the EoS for interacting NADE density in a non-flat universe. In the presence of interaction between NADE and CDM, the EoS parameter of NADE, \(\omega_\Lambda\), behaves like phantom DE in the non-flat FRW universe.

We assumed that the universe to be in thermal equilibrium with the Hawking temperature on the apparent horizon. The apparent horizon is important for the study of cosmology, since on the apparent horizon there is the well known correspondence between the first law of thermodynamics and Einstein equation. We found that for a non-flat universe enclosed by the apparent horizon with the Hawking radiation and containing an interacting NADE with CDM, the generalized second law of gravitational thermodynamics is always respected for any spatial curvature, independently of the EoS parameter of the interacting NADE model. Whereas, the evolution of the entropy of the universe and apparent horizon, separately, depends on the EoS parameter of the model.

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