Holographic dark energy interacting with two fluids and validity of generalized second law of thermodynamics

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Abstract We have considered a cosmological model of holographic dark energy interacting with dark matter and another unknown component of dark energy of the universe. We have assumed two interaction terms \( Q \) and \( Q' \) in order to include the scenario in which the mutual interaction between the two principal components (i.e., holographic dark energy and dark matter) of the universe leads to some loss in other forms of cosmic constituents. Our model is valid for any sign of \( Q \) and \( Q' \). If \( Q < Q' \), then part of the dark energy density decays into dark matter and the rest in the other unknown energy density component. But if \( Q > Q' \), then dark matter energy receives from dark energy and from the unknown component of dark energy. Observation suggests that dark energy decays into dark matter. Here we have presented a general prescription of a cosmological model of dark energy which imposes mutual interaction between holographic dark energy, dark matter and another fluid. We have obtained the equation of state for the holographic dark energy density which is interacting with dark matter and other unknown component of dark energy. Using first law of thermodynamics, we have obtained the entropies for holographic dark energy, dark matter and other component of dark energy, when holographic dark energy interacting with two fluids (i.e., dark matter and other component of dark energy). Also we have found the entropy at the horizon when the radius of the event horizon measured on the sphere of the horizon. We have investigated the GSL of thermodynamics at the present time for the universe enveloped by this horizon. Finally, it has been obtained validity of GSL which implies some bounds on deceleration parameter \( q \).

Keywords Thermodynamics · Dark energy

1 Introduction

Recent observation of the luminosity of type Ia supernovae indicate (Bachall et al. 1999; Perlmutter et al. 1999) an accelerated expansion of the universe and the surveys of clusters of galaxies show that the density of matter is very much less than the critical density. This observation leads to a new type of matter which violate the strong energy condition i.e., \( \rho + 3p < 0 \). The matter content responsible for such a condition to be satisfied at a certain stage of evaluation of the universe is referred to as dark energy (Sahni and Starobinsky 2000; Peebles and Ratra 2003; Padmanabhan 2003; Copeland et al. 2006). This mysterious fluid is believed to dominate over the matter content of the Universe by 70% and to have enough negative pressure as to drive present day acceleration. Most of the dark energy models involve one or more scalar fields with various actions and with or without a scalar field potential (Maor and Brustein 2003; Cardenas and Campo 2004; Ferreira and Joyce 1998). On the other hand when the universe was 380,000 years old neutrinos was 10% atoms i.e. usual baryonic matter was 12%, dark matter was 63%, photons 15% and dark energy was negligible. In the analysis of dark energy the main attraction should be on the state parameter \( w = \frac{p}{\rho} \) where \( p \) and \( \rho \) are the pressure and energy density of the dark energy. In Cosmological constant model \( w = -1 \) around present epoch (Alam et al. 2004) from \( w > -1 \) in the near past (Feng et al. 2005). There are various kinds of models of dark energy and among all of them, the simplest case is the \( \Lambda \)CDM
model. Now, as the observational data permits us to have a rather time varying equation of state, there are a bunch of models characterized by different scalar fields such as a slowly rolling scalar field (Quintessence) (Ratra and Peebles 1988), kinetic energy induced K-essence (Chiba et al. 2000), tachyonic field (Sen 2002), Chaplygin gas (Kamenshchik et al. 2001; Gorini et al. 2004; Debnath et al. 2004), phantom model (Caldwell 2002). In a phantom model, we have the equation of state as \( p = w \rho \), where \( w < -1 \). The simplest type of phantom model is a scalar field having a potential \( V(\phi) \), the kinetic energy of which is negative (Carroll et al. 2003). Also, the current observation data from Type-Ia supernovae and the CMB anisotropy documents give us limits to the various parameters (Hannestad and Mortsell 2002; Melchiori et al. 2003; Spergel et al. 2003; Teegmark et al. 2004) like \( \Omega_B, \Omega_{DE}, \Omega_{DM} \) where \( \Omega \) denotes the relative density and the suffices \( B, DE, DM \) represent baryonic matter, dark energy and dark matter respectively. It also gives us data from which we have the limit \(-1.38 < w < -0.82 \) (Nesseris and Perivolaropoulos 2004) with a very high level of confidence where \( w \) is the equation of state parameter. Recent observations also reveals the fact that our universe is likely to be spatially flat (Bertolami et al. 2004).

The holographic principle emerged in the context of black-holes, where it was noted that a local quantum field theory can not fully describe the black holes (Enqvist et al. 2002). Easther and Lowe (1999) proposed that the holographic principle be replaced by the generalized second law of thermodynamics when applied to time-dependent backgrounds and found that the proposition agreed with the cosmological holographic principle proposed by Fischer and Susskind (1998) for an isotropic open and flat universe with a fixed equation of state. For an effective field theory in a box size \( L \) with UV cutoff \( \Lambda, \) the entropy \( L^3 \Lambda^3. \) Taking the whole universe into account the largest IR cut-off \( L \) is chosen by saturating the inequality so that we get the holographic dark energy density as (Zhang 2005) \( \rho_\Lambda = 3c^2 M_p^2 L^{-2} \) where \( c \) is a numerical constant and \( M_p \equiv 1/\sqrt{8\pi G} \) is the reduced Plank mass. On the basis of the holographic principle proposed by Fischer and Susskind (1998) several others have studied holographic model for dark energy (Gong 2004). Employment of Friedman equation (Setare 2007a) \( \rho = 3M_p^2 H^2 \) where \( \rho \) is the total energy density and taking \( L = H^{-1} \) one can find \( \rho_m = 3(1 - c^2)M_p^2 H^2 \) for flat universe. Thus either \( \rho_m \) or \( \rho_\Lambda \) behaves like \( H^2 \). For small value of \( \Omega_L \) in non-flat universe, Setare and Shafei (2006) have considered a model as a system which departs slightly from flat space. Interaction models where the dark energy weakly interacts with the dark matter have also been studied to explain the evolution of the Universe. This models describe an energy flow between the components. To obtain a suitable evolution of the Universe an interaction is often assumed such that the decay rate should be proportional to the present value of the Hubble parameter for good fit to the expansion history of the Universe as determined by the Supernovae and CMB data (Berger and Shojaei 2006). These kind of models describe an energy flow between the components so that no components are conserved separately. A variety of interacting holographic dark energy models have been proposed and studied for this purpose (Cai and Wang 2005; Zimdahl 2005; Hu and Ling 2006; Setare 2006, 2007b, 2007c, 2007d; Setare and Vagena 2008).

In 1973, Bekenstein (1973) assumed that there is a relation between the event of horizon and the thermodynamics of a black hole, so that the event of horizon of the black hole is a measure of the entropy of it. This idea has been generalized to horizons of cosmological models, so that each horizon corresponds to an entropy. Thus the second law of thermodynamics was modified in the way that in generalized form, the sum of all time derivative of entropies related to horizons plus time derivative of normal entropy must be positive, i.e. the sum of entropies must be increasing function of time. In Einstein gravity, the evidence of connection between black hole thermodynamics and Einstein equations was first discovered in Jacobson (1995) by deriving the Einstein equation from the proportionality of entropy and horizon area together with the first law of thermodynamics \( \delta Q = TdS \) in the Rindler spacetime. For a general static spherically symmetric space–time, Padmanabhan (2002) showed that the Einstein equation at the horizon gives the first law of thermodynamics on the horizon. The thermodynamics in de Sitter space–time was first investigated by Gibbons and Hawking (1977). In a spatially flat de Sitter space–time, the event horizon and the apparent horizon of the Universe coincide and there is only one cosmological horizon. When the apparent horizon and the event horizon of the Universe are different, it was found that the first law and the second law of thermodynamics hold on the apparent horizon, while they break down if one considers the event horizon (Wang et al. 2006). Gong et al. (2007) derived the temperature and entropy of the matter contents inside the apparent horizon from the first law of thermodynamics and discuss the holographic entropy bound and the generalized second law (GSL) of thermodynamics for the Universe with DE. They have addressed the thermodynamics of DE by considering the DE models with constant \( w \) and the generalized Chaplygin gas (GCG).

In the present work, we have considered a cosmological model of holographic dark energy interacting with dark matter and another unknown component of dark energy of the universe. We have assumed two interaction terms \( Q \) and \( Q' \) in order to include the scenario in which the mutual interaction between the two principal components (i.e., holographic dark energy and dark matter) of the universe leads to
some loss in other forms of cosmic constituents. In Sect. 2, we have presented a general prescription of a cosmological model of dark energy which imposes mutual interaction between holographic dark energy, dark matter and another fluid. We have obtained the equation of state for the holographic dark energy density which is interacting with two fluids (i.e., dark matter and other component of dark energy). We have investigated the validity GSL of thermodynamics at the present time for the universe enveloped by the horizon. Finally, we have presented some concluding remarks in Sect. 4.

2 Holographic dark energy interacting with two fluids

Assuming the universe to be homogeneous and isotropic, the Friedmann-Robertson-Walker (FRW) metric can be written as

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

where \(a(t)\) is the expansion scalar or the scale factor and \(k (= 0, \pm 1)\) is the curvature scalar. Then Einstein’s field equations become (choosing \(8\pi G = c = 1\))

\[
3H^2 + \frac{3k}{a^2} = \rho_\Lambda + \rho_m + \rho_X
\]

and

\[
2\dot{H} - \frac{2k}{a^2} = -[(\rho_\Lambda + \rho_m + \rho_X) + (p_\Lambda + p_m + p_X)]
\]

where \(\rho_\Lambda, \rho_m, \rho_X\) and \(p_\Lambda, p_m, p_X\) are respectively energy density and pressure of holographic dark energy, dark matter and another unknown component of dark energy. We will assume that the dark matter component is interacting with the holographic dark energy component, so their continuity equations take the form (Cruz et al. 2008)

\[
\dot{\rho}_\Lambda + 3H(\rho_\Lambda + p_\Lambda) = -Q'
\]

and

\[
\dot{\rho}_m + 3H(\rho_m + p_m) = Q
\]

where \(Q\) and \(Q'\) in order to include the scenario in which the mutual interaction between the two principal components of the universe leads to some loss in other forms of cosmic constituents. In this case, we have assumed \(Q \neq Q'\), so the continuity equation for other component of dark energy becomes

\[
\dot{\rho}_X + 3H(\rho_X + p_X) = Q' - Q
\]

If \(Q < Q'\), then part of the dark energy density decays into dark matter and the rest in the other unknown energy density component. But if \(Q > Q'\), then dark matter energy receives from dark energy and from the unknown component of dark energy.

We are taking about in this case that dark energy decay into dark matter (or vice versa, depending on the sign of \(Q\)) and other component. Assume, the interaction terms \(Q\) and \(Q'\) are (Setare 2007e; Setare and Shafei 2006)

\[
Q = \Gamma_m \rho_\Lambda, \quad Q' = \Gamma_\Lambda \rho_\Lambda
\]

where, \(\Gamma_\Lambda\) is the decaying rate of energy from holographic dark energy to dark matter and other unknown component of dark energy and \(\Gamma_m\) is the receiving rate of energy from holographic dark energy to dark matter only.

Consider the equation of state:

\[
p_\Lambda = w_\Lambda \rho_\Lambda, \quad p_m = w_m \rho_m, \quad p_X = w_X \rho_X
\]

and assume the ratios for energy densities:

\[
r_1 = \frac{\rho_m}{\rho_\Lambda}, \quad r_2 = \frac{\rho_X}{\rho_\Lambda}
\]

So from the above continuity equations, we obtain

\[
\dot{r}_1 = r_1 \Gamma_m + \Gamma_\Lambda + 3H(w_\Lambda - w_m)r_1
\]

and

\[
\dot{r}_2 = (1 + r_2)\Gamma_\Lambda - \Gamma_m + 3H(w_\Lambda - w_X)r_2
\]

Define:

\[
w_{\text{eff}}^m = w_m - \frac{\Gamma_m}{3r_1H}, \quad w_{\text{eff}}^\Lambda = w_\Lambda + \frac{\Gamma_\Lambda}{3H},
\]

so that the continuity equations (4)–(6) become

\[
\dot{\rho}_\Lambda + 3H(1 + w_{\text{eff}}^\Lambda)\rho_\Lambda = 0
\]

and

\[
\dot{\rho}_m + 3H(1 + w_{\text{eff}}^m)\rho_m = 0
\]

and

\[
\dot{\rho}_X + 3H(1 + w_{\text{eff}}^X)\rho_X = 0
\]
Now define the density parameters:

\[
\begin{align*}
\Omega_m &= \frac{\rho_m}{3H^2}, \\
\Omega_\Lambda &= \frac{\rho_\Lambda}{3H^2}, \\
\Omega_X &= \frac{\rho_X}{3H^2}, \\
\Omega_k &= \frac{k}{a^2H^2},
\end{align*}
\] (16)

so from the field equation (2), we obtain

\[
\Omega_m + \Omega_\Lambda + \Omega_X = 1 + \Omega_k
\] (17)

which implies

\[
\dot{\Omega}_m + \dot{\Omega}_X = \dot{\Omega}_k - \dot{\Omega}_\Lambda
\] (18)

From (9) and (17), we have

\[
r_1 = \frac{\Omega_m}{\Omega_\Lambda} = \frac{1 + \Omega_k - \Omega_\Lambda - \Omega_X}{\Omega_\Lambda}
\] (19)

and

\[
r_2 = \frac{\Omega_X}{\Omega_\Lambda} = \frac{1 + \Omega_k - \Omega_\Lambda - \Omega_m}{\Omega_\Lambda}
\] (20)

Now for non-flat universe, the energy density for holographic dark energy is

\[
\rho_\Lambda = 3c^2L^{-2}
\] (21)

where \(c \geq 1\) is a constant and \(L\) represents the radius of the event horizon measured on the sphere of the horizon defined by

\[
L = ar(t)
\] (22)

where \(r(t)\) is a future event horizon obtained from the following equation

\[
r(t) = \frac{\sin y}{\sqrt{k}}
\] (23)

where \(y = \sqrt{k}R_h\), \(R_h\) is the radial size of the event horizon which is measured in \(r\) direction defined by

\[
R_h = a \int_t^\infty \frac{dt}{a}
\] (24)

Now from definition of \(\Omega_\Lambda\) and using (21), we obtain

\[
L = \frac{c}{H\sqrt{\Omega_\Lambda}}
\] (25)

From (21)–(25), we have

\[
\dot{L} = \frac{c}{\sqrt{\Omega_\Lambda}} - \cos y
\] (26)

From (16), (21), (22) and (23), we have

\[
\cos y = \sqrt{1 - \frac{c^2\Omega_\Lambda}{\Omega_\Lambda}}
\] (27)

Using (12), (14), (21) and (27), we get the equation of state for holographic dark energy as

\[
w_\Lambda = -\frac{1}{3} - \frac{2\sqrt{\Omega_\Lambda - c^2\Omega_k}}{3c} - \frac{\Gamma_\Lambda}{3H}
\] (28)

### 3 Generalized second law of thermodynamics

We consider the FRW universe as a thermodynamical system with the horizon surface as a boundary of the system. To study the generalized second law (GSL) of thermodynamics through the universe we deduce the expression for normal entropy using the Gibb’s equation i.e., \(TdS = PdV + dE\), where, \(T, S, P, V\) and \(E\) are respectively temperature, entropy, pressure, volume and internal energy within the event horizon (of radius \(L\) which is measured on the sphere of the horizon) of the universe. The entropies for holographic dark energy, dark matter and other component of dark energy are given by (Setare 2007e; Setare and Shafei 2006)

\[
dS_\Lambda = \frac{1}{T}(P_\Lambda dV + dE_\Lambda)
\] (29)

\[
dS_m = \frac{1}{T}(P_m dV + dE_m)
\] (30)

and

\[
dS_X = \frac{1}{T}(P_X dV + dE_X)
\] (31)

where \(V = \frac{4\pi L^3}{3}\) is the volume containing matter and dark energies with

\[
E_\Lambda = \frac{4\pi L^3}{3} \rho_\Lambda, \quad P_\Lambda = w_\Lambda \rho_\Lambda
\] (32)

\[
E_m = \frac{4\pi L^3}{3} \rho_m, \quad P_m = w_m \rho_m
\] (33)

and

\[
E_X = \frac{4\pi L^3}{3} \rho_X, \quad P_X = w_X \rho_X
\] (34)

Assuming, \(T = \frac{1}{2\pi L}\) and \(x = \log a\) and using (12), (25), (26), (29) and (32), we obtain

\[
\frac{dS_\Lambda}{dx} = \frac{24\pi^2e^2\dot{L}L}{H}\left(w_\Lambda + \frac{\Gamma_\Lambda}{3H} + \frac{1}{3}\right)
\] (35)

\[
\frac{dS_m}{dx} = 8\pi^2\dot{L}\left[\left(\frac{3w_m H - \frac{\Gamma_m}{7}}{t_1}\right)\Omega_m L^2 + \frac{c^2}{\sqrt{\Omega_\Lambda}} - \frac{\Omega_m L}{\Omega_\Lambda H} + \frac{L\Omega_m}{\Omega_\Lambda H} - \frac{L\Omega_m}{\sqrt{\Omega_\Lambda}} \right]
\] (36)
and
\[
\frac{dS_X}{dx} = 8\pi^2 L \left[ \left( 3w_X H + \frac{\Gamma_m - \Gamma_A}{r_2} \right) \Omega_X L^2 \dot{L} + c^2 \left( \frac{\Omega_X \dot{L}}{\Omega_A H} + \frac{L \dot{\Omega}_X}{\Omega_A H} - \frac{L \dot{\Omega}_X}{H \Omega_A} \right) \right] \tag{37}
\]

Now entropy at the horizon is given by
\[
S_L = \pi L^2 \tag{38}
\]
so that from (25) and (26), we obtain
\[
\frac{dS_L}{dx} = \frac{2\pi c}{H^2 \sqrt{\Omega_A}} \left( \frac{c}{\sqrt{\Omega_A}} - \cos \frac{y}{\Omega_A} \right) \tag{39}
\]

From (14), (15), (16) and (21), we have
\[
3w_m H - \frac{\Gamma_m}{r_1} = -H + \frac{\dot{\Omega}_A}{\Omega_A} - \frac{\dot{\Omega}_m}{\Omega_m} - \frac{2H}{c} \sqrt{\Omega_A} \cos y \tag{40}
\]
and
\[
3w_X H + \frac{\Gamma_m - \Gamma_A}{r_2} = -H + \frac{\dot{\Omega}_A}{\Omega_A} - \frac{\dot{\Omega}_X}{\Omega_X} - \frac{2H}{c} \sqrt{\Omega_A} \cos y \tag{41}
\]

Using (16) and (21) and defining the deceleration parameter \( q = -1 - \frac{H}{H_0} \) we can obtain
\[
\dot{\Omega}_k = 2q H \Omega_k \tag{42}
\]
and
\[
\dot{\Omega}_\Lambda = \frac{2\dot{\Omega}_k}{\Omega_k} \left( H \Omega_\Lambda - L^{-1} \dot{L} \Omega_\Lambda + q H \Omega_k \right) \tag{43}
\]

Using (18), (28), (35)–(41) we get,
\[
\frac{d}{dx} (S_\Lambda + S_m + S_X + S_L) = \frac{2\pi L \dot{L}}{H} + 8\pi^2 L^2 \dot{L} \left[ \left( -H + \frac{\dot{\Omega}_A}{\Omega_A} - \frac{2H}{c} \sqrt{\Omega_A} \cos y \right) \times (\Omega_m + \Omega_X) + (\dot{\Omega}_A - \dot{\Omega}_k) \right] + 8\pi^2 c^2 L \left[ \frac{(\Omega_m + \Omega_X) \dot{L}}{\Omega_A H} + \frac{L (\dot{\Omega}_k - \dot{\Omega}_\Lambda)}{\Omega_A H} - \frac{L (\Omega_m + \Omega_X)}{H \Omega_A^2} \dot{\Omega}_\Lambda \right] - 16\pi^2 c L \dot{\Omega}_\Lambda \cos y \tag{44}
\]

Now putting the values of \( L, \dot{L}, \cos y, \Omega_X, \dot{\Omega}_k \) and \( \dot{\Omega}_\Lambda \) from equations (17), (20)–(22), (42) and (43), we finally get
\[
\frac{d}{dx} (S_\Lambda + S_m + S_X + S_L) = \frac{2\pi c}{H^2 \Omega_k \Omega_\Lambda} \left[ -8\pi c (1 + \Omega_k) (\Omega_\Lambda^2 + c^2 \Omega_k^2) + c \Omega_k \Omega_\Lambda (1 + 8\pi (1 + c^2) (1 + \Omega_k)) - \Omega_k \sqrt{\Omega_\Lambda - c^2 \Omega_k} \left( \Omega_\Lambda + 8\pi c^2 (1 + q + \Omega_k) \right) \right] \tag{45}
\]

We have seen that r.h.s. of the expression (44) depends on \( c, H, q, \Omega_k \) and \( \Omega_\Lambda \). At the present time, setting \( c = 1, \Omega_k = 0.01 \) and \( \Omega_\Lambda = 0.72 \), we obtain
\[
\frac{d}{dx} (S_\Lambda + S_m + S_X + S_L) = -\frac{36 + 25q}{H^2} \tag{46}
\]

From the above expression we see that \( \frac{d}{dx} (S_\Lambda + S_m + S_X + S_L) \geq 0 \) if \( q \leq -1.44 \). So in quintessence dominated era and phantom dominated era with \( q > -1.44 \), the GSL cannot be satisfied. But in late stage of phantom dominated era with \( q \leq -1.44 \), the GSL may be satisfied.

4 Discussions

In this work, we have considered FRW model of the universe filled with 3 fluids i.e., holographic dark energy, dark matter and another unknown component of dark energy. We have considered a cosmological model of holographic dark energy interacting with dark matter and another unknown component of dark energy of the universe. We have assumed two interaction terms \( Q \) and \( Q' \) in order to include the scenario in which the mutual interaction between the two principal components (i.e., holographic dark energy and dark matter) of the universe leads to some loss in other forms of cosmic constituents. Our model is valid for any sign of \( Q \) and \( Q' \). If \( Q < Q' \), then part of the dark energy density decays into dark matter and the rest in the other unknown energy density component. But if \( Q > Q' \), then dark matter energy receives from dark energy and from the unknown component of dark energy. Observation suggests that dark energy decays into dark matter. We have presented a general prescription of a cosmological model of dark energy which imposes mutual interaction between holographic dark energy, dark matter and another fluid. We have obtained the equation of state for the holographic dark energy density which is interacting with dark matter and other unknown component of dark energy. Using first law of thermodynamics, we have obtained the entropies for holographic dark energy, dark matter and other component of dark energy, when holographic dark energy interacting with two fluids (i.e., dark matter and other component of dark energy). Also we have found the entropy at the horizon when the radius \( (L) \) of the event horizon measured on the sphere of the horizon. We have investigated the GSL of thermodynamics at the present time for the universe.
enveloped by this horizon. Finally, it has been obtained validity of GSL which implies some bounds on deceleration parameter $q$. But at the present time, $q > -1$, so GSL can not be satisfied in our model, but in late stage of phantom dominated era, the GSL may be satisfied.

Acknowledgements The author is thankful to IUCAA, Pune, India for providing Associateship Programme under which part of the work was carried out. The author also thanks to the members of Relativity and Cosmology Research Centre, Jadavpur University, India for some illuminating discussions.

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