Holographic Dark Energy Model with Modified Variable Chaplygin Gas

B. C. Paul*
Physics Department, North Bengal University,
Siliguri, Dist. : Darjeeling, Pin : 734 013, West Bengal, India

Abstract

In this letter we consider a correspondence between holographic dark energy and variable modified Chaplygin gas to obtain a holographic dark energy model of the universe. The corresponding potential of the scalar field has been reconstructed which describes the variable Chaplygin gas. The stability of the holographic dark energy in this case is also discussed.

*Electronic mail : bcpaul@iucaa.ernet.in
1 Introduction:

Recent cosmological observations namely, high redshift surveys of type Ia Supernovae, WMAP, CMB etc. predict that the present universe is passing through an accelerating phase of expansion [1]. It has also been predicted from COBE that the present universe might have emerged from an inflationary phase in the early universe. The above two observational facts in the universe do not find explanation in the framework of Einstein general theory of Relativity (GTR) with normal matter. It is known that early inflation may be realized in a semiclassical theory of gravity where matter is described by quantum fields [2]. Starobinsky obtained inflationary solution considering a curvature squared term in the Einstein-Hilbert action [3] long before the advent of inflation was known. However, the efficacy of inflation is known only after the seminal work of Guth who first employed the phase transition mechanism to accommodate inflation. Thereafter more than a dozen of inflationary model came up. In some of these inflation is realized by (i) a modification of gravitational sector of action introducing higher order terms or [4], (ii) a modification of the matter sector taking into account scalar fields. In the later case inflation is obtained with an equation of state \( p = \omega \rho \), if \( \omega = -1 \), but the present accelerating phase can be realized with \( \omega < -1 \). The usual fields in the standard model of particle physics are not suitable to obtain such accelerating phase of the universe. In fact it is a challenge to theoretical physics to describe the origin of such matter density. Recent astronomical observations predict that dark energy content of the universe is about 76 % of the total energy density of the universe. To accommodate such a huge energy density various kinds of exotic matters are considered as possible candidate for the dark energy. Chaplygin gas is one such candidate with an equation of state (EOS) \( p = -\frac{B}{\rho} \) [5], where \( \rho \) and \( p \) are the energy density and pressure respectively and \( B \) is a constant. Subsequently, a modified
form of the equation of state $p = -\frac{B}{\rho}$ with $0 \leq \alpha \leq 1$ was also considered to construct a viable cosmological model [6, 7], which is known as generalized Chaplygin gas (GCG). It has two free parameters $B$ and $\alpha$ respectively. The EOS for GCG has been further modified to $p = A\rho - \frac{B}{\rho^\alpha}$, with $0 \leq \alpha \leq 1$ which is known as modified GCG [8, 9]. In a flat Friedmann model it is shown [6] that the modified generalized Chaplygin gas may be equivalently described in terms of a homogeneous minimally coupled scalar field $\phi$. Barrow [10] has outlined a method to fit Chaplygin gas in FRW universe. Gorini et al. [11] using the above scheme obtained the corresponding homogeneous scalar field $\phi(t)$ in a potential $V(\phi)$ which can be used to obtain a viable cosmological model with modified Chaplygin gas. Another form of EOS for Chaplygin gas [12] is considered recently which is given by

$$p = A\rho - \frac{B(a)}{\rho^\alpha} \quad with \quad 0 \leq \alpha \leq 1,$$

(1)

with a variable $B = B_o a^{-3n}$, $B_o$ is a constant and $a$ is the scale factor of the universe. Guo and Zhang [13] obtained cosmological model using the EOS for variable Chaplygin gas. Cosmological observational results are used to study the constraints [14]

Recently holographic principle [15, 16] is incorporated in cosmology [17-20] to track the dark energy content of the universe following the work of Cohen et al. [21]. Holographic principle is a speculative conjecture about quantum gravity theories proposed by G’t Hooft. The idea is subsequently promoted by Fischler and Susskind [15] claiming that all the information contained in a spatial volume may be represented by a theory that lives on the boundary of that space. For a given finite region of space it may contain matter and energy within it. If this energy be less than a critical value then the region collapses to a black hole. As a black hole is known theoretically to have an entropy which is proportional to its surface area of its event horizon. A black hole event horizon encloses a volume, thus a more
massive black hole have larger event horizon and encloses larger volume. The most massive black hole that can fit in a given region is the one whose event horizon corresponds exactly to the boundary of the given region under consideration. The maximal limit of entropy for an ordinary region of space is directly proportional to the surface area of the region and not to its volume. Thus, according to holographic principle, under suitable conditions all the information about a physical system inside a spatial region is encoded in the boundary. The basic idea of a holographic dark energy in cosmology is that the saturation of the entropy bound may be related to an unknown ultra-violet (UV) scale \( \Lambda \) to some known comological scale in order to enable it to find a viable formula for the dark energy which may be quantum gravity in origin and it is characterized by \( \Lambda \). The choice of UV-Infra Red (IR) connection from the covariant entropy bound leads to a universe dominated by blackhole states. According to Cohen et al. [21] for any state in the Hilbert space with energy \( E \), the corresponding Schwarzschild radius \( R_s \sim E \), may be less than the IR cut off value \( L \) (where \( L \) is a cosmological scale). It is possible to derive a relation between the UV cutoff \( \rho_\Lambda^{1/4} \) and the IR cutoff which eventually leads to a constraint \( \left( \frac{8\pi G}{c^2} \right) L^3 \left( \rho_\Lambda \right) \leq L \) [22] where \( \rho_\Lambda \) is the energy density corresponding to dark energy characterized by \( \Lambda \), \( G \) is Newton’s gravitational constant and \( c \) is a parameter in the theory. The holographic dark energy density is

\[
\rho_\Lambda = 3c^2 M_P^2 L^{-2}, \tag{2}
\]

where \( M_P^2 = 8\pi G \). It is known that the present acceleration may be described if \( \omega_\Lambda = \frac{\rho_\Lambda}{\rho_\Lambda} < -\frac{1}{3} \). If one considers \( L \sim \frac{1}{H} \) it gives \( \omega_\Lambda = 0 \). A holographic cosmological constant model based on Hubble scale as IR cut off does not permit accelerating universe. It is also examined [17] that the holographic dark energy model based on the particle horizon as the IR cutoff is not suitable for an accelerating universe. However, an alternative model of dark energy using particle horizon in closed model is also proposed [23]. Li [18] has obtained
an accelerating universe considering event horizon as the cosmological scale. The model is consistent with the cosmological observations. Thus to have a model consistent with observed universe one should adopt the covariant entropy bound and choose $L$ to be event horizon [24]. Considering a correspondence of holographic dark energy and Chaplygin gas the field potential is reconstructed [25, 26]. In this paper we consider EOS given by (1) and set up a correspondence with holographic dark energy to reconstruct scalar field potential.

The paper is organized as follows: in sec. 2, the relevant field equation with modified variable Chaplygin gas in FRW universe is presented. Considering correspondence of holographic dark energy fields with modified variable chaplygin gas, we determine the field and the corresponding potential is reconstructed. in sec. 3, squared speed of sound for holographic dark energy is evaluated for stability analysis. Finally in sec. 4, a brief discussion is given.

2 Field Equation and Modified Variable Chaplygin Gas:

The Einstein’s field equation is given by

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu}$$

(3)

where $T_{\mu\nu}$ is the energy momentum tensor.

We consider a Robertson-Walker (RW) metric given by

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

(4)

where $a(t)$ is the scale factor of the universe. The energy momentum tensor is $T^\mu_\nu = (\rho, p, p, p)$ where $\rho$ and $p$ are energy density and pressure respectively.

Using RW metric (4) and the energy momentum tensor, the Einstein’s field equation (3) yields

$$H^2 + \frac{k}{a^2} = \frac{1}{3M_P^2}\rho$$

(5)
where we use $8\pi G = M_P^2$. The conservation equation for matter is given by

$$
\frac{d\rho}{dt} + 3H(\rho + p) = 0 \tag{6}
$$

where $\rho = \rho_{\text{matter}} + \rho_\Lambda$. For modified variable chaplygin gas (henceforth, VCG), we use EOS given by eq. (2) in eq. (6), which yields

$$
\rho_\Lambda = \left( \frac{(1 + \alpha)B_0}{(1 + \alpha)(1 + A) - n a^{3n}} - \frac{1}{a^{3n}} + \frac{C_o}{a^m} \right)^{\frac{1}{1+\alpha}} \tag{7}
$$

where $C_o$ is an integration constant and we denote $m = 3(1 + A)(1 + \alpha)$. We now define the following

$$
\Omega_\Lambda = \frac{\rho_\Lambda}{\rho_{cr}}, \quad \Omega_m = \frac{\rho_m}{\rho_{cr}}, \quad \Omega_k = \frac{k}{a^2 H^2} \tag{8}
$$

where $\rho_{cr} = 3M_P^2 H^2$, $\Omega_\Lambda$, $\Omega_m$ and $\Omega_k$ represent density parameter corresponding to $\Lambda$, matter and curvature respectively.

We assume here that the origin of dark energy is a scalar field. Making use of Barrow’s scheme [10], we get the following

$$
\rho_\phi = \frac{1}{2} \dot{\phi}^2 + V(\phi) = \rho = \left( \frac{B_1}{a^{3n}} + \frac{C_o}{a^m} \right)^{\frac{1}{\alpha+1}}, \tag{9}
$$

$$
p_\phi = \frac{1}{2} \dot{\phi}^2 - V(\phi) = p = \frac{(n-1-\alpha)B_1}{(n+1)a^{3n}} + \frac{AC_o}{a^m} \left( \frac{B_1}{a^{3n}} + \frac{C_o}{a^m} \right)^{\frac{1}{\alpha+1}}, \tag{10}
$$

where $B_1 = \frac{(1+\alpha)B_O}{(1+\alpha)(1+A)-n}$. Now the corresponding scalar field potential and its kinetic energy term is obtained from above which are given by

$$
V(\phi) = \frac{C_o(1-A)}{2a^m} + \frac{1+\alpha-n}{1+\alpha} \frac{B_1}{a^{3n}}, \tag{11}
$$

$$
\dot{\phi}^2 = \frac{nB_1}{(1+\alpha)a^{3n}} + \frac{C_o(1+A)}{a^m} \left( \frac{B_1}{a^{3n}} + \frac{C_o}{a^m} \right)^{\frac{1}{\alpha+1}} \tag{12}
$$

The above equation reduces to that obtained in Ref. [26] for $\alpha = 1$, $A = 0$ and $n = 0$ and that obtained in Ref. [27] for $n = 0$. Now we consider that the scalar field model of
dark energy described by modified variable Chaplygin gas corresponds to holographic dark energy of the universe. In this section we reconstruct the corresponding potential. Let us now consider a non-flat universe with \( k \neq 0 \) and use the holographic dark energy density given in (2) as

\[
\rho_\Lambda = 3c^2 M_P^2 L^{-2},
\]

(13)

where \( L \) is the cosmological length scale for tracking the field corresponding to holographic dark energy in the universe. The parameter \( L \) is defined as

\[
L = ar(t).
\]

(14)

where \( a(t) \) is the scale factor of the universe and \( r(t) \) is relevant to the future event horizon of the universe. Using Robertson-Walker metric one gets [19]

\[
L = \frac{a(t)}{\sqrt{|k|}} \sin \left[ \sqrt{|k| R_h(t)/a(t)} \right] \quad \text{for} \quad k = +1,
\]

\[
= R_h \quad \text{for} \quad k = 0,
\]

\[
= \frac{a(t)}{\sqrt{|k|}} \sinh \left[ \sqrt{|k| R_h(t)/a(t)} \right] \quad \text{for} \quad k = -1.
\]

(15)

where \( R_h \) represents the event horizon which is given by

\[
R_h = a(t) \int_t^\infty \frac{dt'}{a(t')} = a(t) \int_0^{r_1} \frac{dr}{\sqrt{1 - kr^2}}.
\]

(16)

Here \( R_h \) is measured in \( r \) direction and \( L \) represents the radius of the event horizon measured on the sphere of the horizon. Using the definition of \( \Omega_\Lambda = \frac{\rho_\Lambda}{\rho_{cr}} \) and \( \rho_{cr} = 3M_P^2 H^2 \), one can derive [20]

\[
HL = \frac{c}{\sqrt{\Omega_\Lambda}}.
\]

(17)

Using eqs. (16)- (17), we determine the rate of change of \( L \) with respect to \( t \) which is

\[
\dot{L} = \frac{c}{\sqrt{\Omega_\Lambda}} - \frac{1}{\sqrt{|k|}} \cos \left( \frac{\sqrt{|k|} R_h}{a(t)} \right) \quad \text{for} \quad k = +1,
\]
\[
\frac{c}{\sqrt{\Omega_\Lambda}} - 1 \quad \text{for } k = 0, \\
\frac{c}{\sqrt{\Omega_\Lambda}} - \frac{1}{\sqrt{|k|}} \cosh \left( \frac{\sqrt{|k|} R_h}{a(t)} \right) \quad \text{for } k = -1. \tag{18}
\]

Using eqs. (13) - (18), we obtain the holographic energy density \(\rho_\Lambda\), which is given by

\[
\frac{d\rho_\Lambda}{dt} = -2H \left[ 1 - \frac{\sqrt{\Omega_\Lambda}}{c} \frac{1}{\sqrt{|k|}} f(X) \right] \rho_\Lambda, \tag{19}
\]

here we use the notation, henceforth,

\[
f(X) = \cos(X) \quad [1, \cosh(X)] \quad \text{for } k = 1 \quad [0, -1], \tag{20}
\]

with \(X = \frac{R_h}{a(t)}\). The energy conservation equation is

\[
\frac{d\rho_\Lambda}{dt} + 3H(1 + \omega_\Lambda)\rho_\Lambda = 0 \tag{21}
\]

which is used to determine the equation of state parameter

\[
\omega_\Lambda = - \left( \frac{1}{3} + 2\sqrt{\Omega_\Lambda} \frac{3c}{f(X)} \right). \tag{22}
\]

Now we assume holographic dark energy density which is equivalent to the modified variable Chaplygin gas energy density. The corresponding energy density may be obtained using eq. (7). The EOS parameter follows from eq. (1)

\[
\omega = \frac{p}{\rho} = A - \frac{B(a)}{\rho^{\alpha+1}}. \tag{23}
\]

We now consider correspondence between the holographic dark energy and modified Chaplygin gas energy density. Using eqs. (7), (13) and (19), one obtains

\[
B_o = (3c^2M_P^2L^{-2})^{\alpha+1} a^{3n} \left[ A + \frac{1}{3} + 2\sqrt{\Omega_\Lambda} \frac{3c}{f(X)} \right], \tag{24}
\]

\[
C_o = (3c^2M_P^2L^{-2})^{\alpha+1} a^m \left[ 1 - \frac{(1 + \alpha)\left( A + \frac{1}{3} + 2\sqrt{\Omega_\Lambda} \frac{3c}{f(X)} \right)}{(1 + \alpha)(A+1) - n} \right]. \tag{25}
\]
Consequently one determines the scalar field potential which is given by

\[ V(\phi) = \frac{3c^2M^2_P L^{-2}}{2} \left[ 1 - A + \frac{(1 + \alpha)(1 + A) - 2n}{(1 + \alpha)(1 + A) - n} \left( A + \frac{1}{3} + \frac{2\sqrt{\Omega_\Lambda}}{3} f(X) \right) \right], \]  

(26)

and the corresponding kinetic energy of the field is

\[ \dot{\phi}^2 = 2c^2M^2_P L^{-2} \left[ 1 - \frac{\sqrt{\Omega_\Lambda}}{c} f(X) \right]. \]  

(27)

It is interesting to note that for \( n = 0 \) the potential reduces to the form that obtained by Paul et al. [27] and for \( n = 0 \) and \( A = 0 \), it reduces to that form obtained by Setare [25] (where \( B_o \) is to be replaced by \( A \)). We now substitute \( x = \ln a(t) \), to transform the time derivative to the derivative with logarithm of the scale factor, which is the most useful function in this case. Consequently from eq. (27) one obtains

\[ \dot{\phi}' = M_P \sqrt{2\Omega_\Lambda \left( 1 - \frac{\sqrt{\Omega_\Lambda}}{c} f(X) \right)} \]  

(28)

where \( ()' \) prime represents derivative with respect to \( x \). Thus, the evolution of the scalar field is given by

\[ \phi(a) - \phi(a_o) = \sqrt{2}M_P \int_{\ln a_o}^{\ln a} \sqrt{\Omega_\Lambda \left( 1 - \frac{\sqrt{\Omega_\Lambda}}{c} f(X) \right)} \, dx. \]  

(29)

3 Squared speed for Holographic Dark Energy:

We consider a closed universe model \((k = 1)\) in this case. The dark energy equation of state parameter given by eq. (29) reduces to

\[ \omega_\Lambda = -\frac{1}{3} \left( 1 + \frac{2\sqrt{\Omega_\Lambda}}{c} \cos y \right) \]  

(30)

where \( y = \frac{R_H a(t)}{a(t)} \). The minimum value it can take is \( \omega_{\text{min}} = -\frac{1}{3} \left( 1 + 2\sqrt{\Omega_\Lambda} \right) \) and one obtains a lower bound \( \omega_{\text{min}} = -0.9154 \) for \( \Omega_\Lambda = 0.76 \) with \( c = 1 \). Taking variation of the state parameter with respect to \( x = \ln a \), we get [17]

\[ \frac{\Omega'_\Lambda}{\Omega_\Lambda^2} = (1 - \Omega_\Lambda) \left( \frac{2}{c} \frac{1}{\Omega_\Lambda} \cos y + \frac{1}{1 - a^2 \gamma} \right) \]  

(31)
and the variation of equation of state parameter becomes

\[
\omega'_\Lambda = -\frac{\sqrt{\Omega_\Lambda}}{3c} \left[ \frac{1 - \Omega_\Lambda}{1 - \gamma a} + \frac{2\sqrt{\Omega_\Lambda}}{c} \left( 1 - \Omega_\Lambda \cos^2 y \right) \right], \tag{32}
\]

where \( \gamma = \frac{\Omega_\Lambda}{\Omega_m} \). We now introduce the squared speed of holographic dark energy fluid as

\[
v^2_\Lambda = \frac{d p_\Lambda}{d \rho_\Lambda} = \frac{\dot{p}_\Lambda}{\rho_\Lambda} = \frac{p'_\Lambda}{\rho'_\Lambda}, \tag{33}
\]

where variation of eq. (30) w.r.t. \( x \) is given by

\[
p'_\Lambda = \omega'_\Lambda \rho_\Lambda + \omega_\Lambda \rho'_\Lambda. \tag{34}
\]

Using the eqs. (41) and (42) we get

\[
v^2_\Lambda = \omega'_\Lambda \frac{\rho_\Lambda}{\rho'_\Lambda} + \omega_\Lambda
\]

which now becomes

\[
v^2_\Lambda = -\frac{1}{3} - \frac{2}{3c} \sqrt{\Omega_\Lambda} \cos y + \frac{1}{6c} \sqrt{\Omega_\Lambda} \left[ \frac{1 - \Omega_\Lambda}{1 - \gamma a} + \frac{2}{c} \sqrt{\Omega_\Lambda} \left( 1 - \Omega_\Lambda \cos^2 y \right) \right]. \tag{35}
\]

The variation of \( v^2_\Lambda \) with \( \Omega_\Lambda \) is shown in fig. 2 for different \( y \) values. It is found that for a given value of \( c, a, \gamma \), the model admits a positive squared speed for \( \Omega_\Lambda > 0 \). However, \( \Omega_\Lambda \) is bounded below otherwise instability develops. We note also that for \( \frac{(2n+1)\pi}{2} < y < \frac{(2n+3)\pi}{2} \), (where \( n \) is an integer) no instability develops. We plot the case for \( n = 0 \) in fig. 2, it is evident that for \( y \leq \frac{\pi}{2} \) and \( y \geq \frac{3\pi}{2} \), the squared speed for holographic dark energy becomes negative which led to instability. But for the region \( \frac{\pi}{2} < y < \frac{3\pi}{2} \) with \( n = 0 \) no such instability develops. It is also found that for \( y = 0 \) i.e., in flat case the holographic dark energy model is always unstable [28].
Figure 1: shows the plot of $v_{\Lambda}^2$ versus $\Omega_{\Lambda}$ for different values of $y$ with $c = 1$, $\gamma = 1/3$ and $a = 1$, in the first array the figures are for $y = \frac{\pi}{3}$ and $y = \frac{\pi}{2}$, in the second array for $y = \frac{1.5\pi}{2}$, $y = \pi$ and in the third array for $y = \frac{2.5\pi}{2}$, $y = \frac{3\pi}{2}$.
4 Discussions:

In this paper we explored holographic dark energy model in a FRW universe with a scalar field which describe the modified variable Chaplygin gas. We consider correspondence of holographic dark energy and the modified variable Chaplygin gas to reconstruct the potential. Since a complete theory of quantum gravity is yet to emerge, we adopt the above approach to understand the nature of dark energy. We determine the evolution of the field and reconstruct the potential of the Holographic dark energy in the case of flat, closed and open models of the universe. Although the cosmological observations predict a flat model of the universe, a closed universe with small positive curvature ($\Omega_k = 0.01$) is compatible with observations. So, in this paper we considered non-flat case also. We give here a generalized expression for the potential and the kinetic energy term considering a modified variable Chaplygin gas [12, 13]. The holographic dark energy field and the corresponding potential depend on three parameters namely, $A$, $\alpha$ and $n$. The potential and the kinetic energy given by eqs. (11) and (12) reduce to that form obtained by Setare [26] for $A = 0$, $n = 0$ and $\alpha = 1$. However, the result obtained by Paul et al. [27] recovered for $n = 0$. The stability of the holographic dark energy is studied in sec. 3 and found that the stability depends on the parameter $\Omega_\Lambda$. The evolution of the holographic dark energy field follows samepattern in the modified Chaplygin gas, generalized Chaplygin gas and in the variable Chaplygin gas. However, the field potential is differs, which depends on the EOS parameters $A = 0$, $n = 0$ and $\alpha = 1$. It is found that holographic field potential $V(\phi)$ become a constant for $n = \frac{(1+\alpha)(1+A)}{2}$. A free holographic field is permitted for the case $A = 1$ and $n = 1 + \alpha$.

Acknowledgement:

Author would like to thank IUCAA, Pune and IRC, Physics Department, North Bengal.
University (NBU) for providing facilities to initiate the work. BCP is thankful to the Third World Academy of Sciences (TWAS), Italy for Associateship to support a visit to the Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing and University Grants Commission, New Delhi for financial support to carry out the work.
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