Higher order corrections of the extended Chaplygin gas cosmology with varying $G$ and $\Lambda$

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Abstract

In this paper we study two different models of dark energy based on Chaplygin gas equation of state. The first model is variable modified Chaplygin gas and the second one is extended Chaplygin gas. Both cases considered in higher order $f(R)$ gravity. Also we consider varying $G$ and $\Lambda$ in both models. We investigate some cosmological parameters such as Hubble expansion, deceleration and equation of state parameters. Then we compare our results with observational data and find that the extended Chaplygin gas model including higher order corrections with varying $G$ and $\Lambda$ is a good model to describe universe.

Keywords: $f(R)$ Gravity; Dark Energy; Cosmology.

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1 Introduction

Dark energy may explain the origin of the accelerated expansion of universe [1, 2]. There are several models to describe the dark energy such as the models based on quintessence [3, 4]. Another interesting candidate is Einstein’s cosmological constant which has two crucial problems which called fine tuning and coincidence [5], therefore people seek another models. There are also other interesting models to describe the dark energy such as $k$-essence model [6] and tachyonic model [7].

There is a successful model to describe dark energy which is based on is Chaplygin gas (CG) equation of state [8, 9]. However, pure CG model is not consistent with observational data [10-13]. Hence, generalized Chaplygin gas (GCG) model proposed [14]. This model indeed unified both dark matter and dark energy. It is also possible to study possiblity of viscosity in GCG [15-20]. However, observational data ruled out such a proposal, and the modified Chaplygin gas (MCG) model introduced [21]. Recently, viscous MCG is also suggested and studied [22, 23]. A further extension of CG model is called modified cosmic Chaplygin gas (MCCG) which was proposed recently [24-27]. Also, various Chaplygin gas models were studied from the holography point of view [28-30].
The MCG equation of state (EoS) has two parts, the first term gives an ordinary fluid obeying a linear barotropic EoS, and the second term relates pressure to some power of the inverse of energy density. Therefore, essentially we are dealing with a two-fluid model. However, it is possible to consider barotropic fluid with quadratic EoS or even with higher orders EoS [31, 32]. Therefore, it is interesting to extend MCG EoS which recovers at least barotropic fluid with quadratic EoS. We called the new version as extended Chaplygin gas (ECG) model. Also, it is interesting to develop ordinary models to obtain more agreement with observational data which may be yields by variation of constant in EoS parameter.

In order to obtain a comprehensive model we also add two modifications to the ordinary model. First, we consider a fluid which governs the background dynamics of the universe in a higher derivative theory of gravity. Second, we consider varying $G$ and $\Lambda$. As we know the Einstein equations of general relativity do not permit any variations in the gravitational constant $G$ and cosmological constant $\Lambda$ because of the fact that the Einstein tensor has zero divergence and energy conservation law is also zero. So, some modifications of Einstein equations are required. Similar study recently performed for another fluid model instead of Chaplygin gas [33]. Also there are several study on cosmological models with varying $G$ and $\Lambda$ [34-38]. Therefore, in this paper we study two different model of Chaplygin gas models in higher order gravity with varying $G$ and $\Lambda$. This paper is organized as the follows. In section 2 we introduce our models. In section 3 we study special case of constant $G$ and $\Lambda$. Then in section 4 we investigate cosmological parameters of our two models. In section 5 we give statefinder diagnostics for both models and finally in section 6 we give conclusion.

2 The models

We consider two different models for a fluid which governs the background dynamics of the Universe in a higher derivative theory of gravity in the presence of time varying $G$ and $\Lambda$. Within modified theories of gravity we hope to solve the problems of the dark energy which are originated from general relativity. A gravitational action with higher order term in the scalar curvature $R$ containing a variable $G(t)$ given by,

$$I = -\int \left[ \frac{1}{16\pi G} f(R) + L_m \right] \sqrt{-g} d^4x,$$ (1)

where $f(R)$ is a function of $R$ and its higher power including a variable $\Lambda$. Also, $g$ is the determinant of the four dimensional metric and $L_m$ represents the matter Lagrangian. Considering the second order gravity gives the following function,

$$f(R) = R + \alpha R^2 - 2\Lambda.$$ (2)

By using the following flat FRW metric,

$$ds^2 = -dt^2 + a(t)^2 (dr^2 + r^2 d\Omega^2),$$ (3)

we get [39],

$$H^2 - 6\alpha(2H\dot{H} - \dot{H}^2 + 6\dot{H}H^2) = \frac{8\pi G \rho}{3} + \frac{\Lambda}{3},$$ (4)

where $d\Omega^2 = d\theta^2 + \sin^2 \theta d\phi^2$ is the angular part of the metric and $a(t)$ represents the scale factor. The $\theta$ and $\phi$ parameters are the usual azimuthal and polar angles of spherical coordinates, with $0 \leq \theta \leq \pi$ and $0 \leq \phi < 2\pi$.

Energy conservation reads as,

$$\dot{\rho} + 3H(\rho + P) = -\left( \frac{\dot{G}}{G} \rho + \frac{\dot{\Lambda}}{8\pi G} \right),$$ (5)

where $\rho$ and $P$ are the energy density and pressure of the perfect fluid respectively. Modified theories of gravity like $f(R)$ theories give us possibility to find a natural representation and introduction of the dark energy into theory. Comparing Eq.(13) with the field equations in general relativity yields to associate $6\alpha(2H\dot{H} - \dot{H}^2 + 6\dot{H}H^2)$ to the energy density of dark energy. Therefore, the type of the dark energy and
dynamics of the universe depends on the form of \( f(R) \) which will be considered. The type of the work which we would like to consider in this paper assume an existence of an effective fluid controlling the dynamics of the universe composed non-interacting dark energy (from \( f(R) \)) and a fluids from our assumptions. In forthcoming articles we will consider different interactions considered in literature. As there is not interaction for mater we have,

\[
\dot{\rho} + 3H(\rho + P) = 0.
\]

Therefore, for the dynamics of \( G \) we will have,

\[
\dot{G} + \frac{\dot{\Lambda}}{8\pi\rho} = 0.
\]

The energy density \( \rho \) assumed some kinds of Chaplygin gas. MCG is described by the following EoS,

\[
p = A\rho - \frac{B}{\rho^n},
\]

where \( A \) and \( B \) are positive constants.

It is possible to consider \( B \) as a variable instead of a constant. So, a varying MCG is given by [40, 41],

\[
P = A\rho - \frac{B(t)}{\rho^n},
\]

where,

\[
B(t) = \omega(t)a(t)^{-3(1-\omega(t))(1-n)},
\]

with,

\[
\omega(t) = \omega_0 + \omega_1t\frac{\dot{H}}{H}.
\]

This is our first model while in the second model we consider the extended Chaplygin gas EoS,

\[
P = \sum_{k=1}^{m} A_k \rho^k - \frac{B}{\rho^n},
\]

where \( A_k = 1/k, B \) and \( n \) are positive constants. The ECG EoS reduces to the MCG EoS for \( k = 1 \), and can recover barotropic fluid with quadratic EoS by setting \( k = 2 \). Also, higher \( k \) may recover higher order barotropic fluid which is indeed our motivation to suggest extended Chaplygin gas.

### 3 Numerical results with constant \( G \) and \( \Lambda \)

We start models analysis from the constant \( \Lambda \) and \( G \) (\( 8\pi G = c = 1 \)) cases. Therefore, we have the following two equations, which will describe the dynamics of the universe, in this case the dynamics of the Chaplygin gases described by the following equation,

\[
H^2 - 6\alpha(2H\dot{H} - \dot{H}^2 + 6\dot{H}H^2) = \frac{\rho}{3} + \frac{\Lambda}{3}.
\]

and,

\[
\dot{\rho} + 3H(\rho + P) = 0.
\]

In the first model which is given by the EoS (9) we obtain the behavior of Hubble expansion parameter and \( \omega = P/\rho \) by using the numerical analysis in Fig. 1. The left plot of Fig. 1 shows typical time evolution of the Hubble expansion parameter. It is found that increasing \( \Lambda \) decreases value of \( H \). For the cases of \( \Lambda < 2.5 \), Hubble parameter is increasing function of time. \( \Lambda = 2.5 \) yields to the constant \( H \) and for the cases of \( \Lambda > 2.5 \), Hubble parameter is decreasing function of time. However, we expected that the Hubble parameter decreases with time and yields to a constant value at the present epoch. Therefore, this model
has not good agreement with observational data. However, the evolution of the EoS parameter (right plot of Fig. 1) agrees with the ΛCDM model and other models where $\omega \to -1$ is expected. Using Fig. 1, we can fit the function of Hubble expansion parameter as the following,

$$H = H_0 + C(2.5 - \Lambda)t,$$

(15)

where $H_0$ is the current value of the Hubble parameter and $C$ is a constant. Therefore, we can investigate the deceleration parameter $q$ via the following relation:

$$q = -1 - \frac{H}{H^2}.$$

(16)

Numerical analysis yields to Fig. 2 which shows that, for appropriate values of parameters involved, we obtain $q = -1$ which is in agreement with the ΛCDM model. In Fig. 2 we also can see deceleration to acceleration and acceleration to deceleration phase transitions. Curves of this figure drawn for $\Lambda \geq 2.5$, however in the cases of $\Lambda \leq 2.5$ we find $q \leq -1$.

![Figure 1: Behavior of $H$ and $P/\rho$ against $t$.](image)

![Figure 2: Behavior of $q$ against $t$. $\Lambda = 2.5$ (orange), $\Lambda = 3.5$ (red), $\Lambda = 4$ (green), $\Lambda = 5$ (black).](image)

Analysis of the second model with EoS given by Eq. (12) based on the following EoS parameter,

$$\omega = \sum_{k=1}^{m} A_k \rho^{k-1} - \frac{B}{\rho^{n+1}},$$

(17)

to the third order ($m = 3$) presented in Fig. 3. We can see similar behavior with the first model. Therefore, we should apply a great modification to obtain results more agree with observations. For this reason we will consider varying $G$ and $\Lambda$ in the next section.
4 Numerical results with varying $G$ and $\Lambda$

To perform analysis of the dynamic of the universe, we also assume that the form of $\Lambda$ is given. In order to escape future confusions and not to complicate the writing and the analysis of the work, we assumed that the form of an effective $\Lambda$ is given as follow,

$$\Lambda = \gamma \rho,$$

where $\gamma$ is a positive constants. Therefore, for the dynamics of $G$ we will have,

$$\dot{G} + \frac{\gamma \dot{\rho}}{8\pi \rho} = 0. $$

The last equation can be integrated easily and for $G$ we will have, 

$$G = G_0 - \frac{\gamma}{8\pi} \ln \rho,$$

where $G_0$ is an integration constant. In the following subsections, we give numerical analysis of our two models.

4.1 Variable modified Chaplygin gas model

Within this subsection we analyze our first model, which is a varying modified Chaplygin gas with EoS,

$$\omega = A - \frac{B(t)}{\rho^{n+1}}.$$

where we used Eq. (9).

The plots of Fig. 4 show that the Hubble parameter in this model is decreasing function of time and yields to a constant at the late time. The first plot shows that increasing $\alpha$ increases value of $H$, therefore we find that the effect of higher order terms of gravity is increasing of Hubble expansion parameter. The second plot deals with variation of parameter $A$. It has been shows that increasing $A$ increases value of $H$. The third plot show variation of Hubble expansion parameter with $n$. It is clear that the variation of $H$ depends on time. In the cases of $t < 5$, increasing $\alpha$ increases value of $H$ but in the cases of $t > 5$, increasing $\alpha$ decreases value of $H$. Finally, in the last plot we can see variation of $H$ with $\omega_0$ and $\omega_1$.

In the plots of Fig. 5 we can see evolution of the deceleration parameter with variation of $\alpha$, $A$, $n$, $\omega_0$ and $\omega_1$. In all cases we can see that $-1 < q < 0$ which is agree with current observational data. In this case there is no acceleration to deceleration phase transition.

In Fig. 6 we drawn EoS parameter versus time. We can see from the first plot that increasing $\alpha$ decreases value of $\omega = P/\rho$. It is illustrated that higher values of $\alpha$ makes $\omega \to -1$ faster than lower values of $\alpha$. Similar situation happen by variation of $A$ (at least for the late time behavior). The third plot of Fig. 6 show variation of $\omega$ with $n$. The first and second plots drawn for $n = 0.1$ and $n = 0.3$ respectively which yield to $\omega$ as totally decreasing function of time. But, for the higher values of $n$ the situation is different, as illustrated in the third plot of Fig. 6. The
Plots of Fig. 7 show agreement with constraint (22).

Finally, in Fig. 7 we draw variation of \( \dot{G}/G \) against time. According to the most observational data, one can write \([42]\),

\[
\frac{\dot{G}}{G} \leq 1.3 \times 10^{-12} \text{yr}^{-1}.
\]

(22)

Plots of Fig. 7 show agreement with constraint (22).

Therefore, apart behavior of the deceleration parameter we conclude that the first model agree with observational data.

### 4.2 Extended Chaplygin gas model

In the second model we use the EoS parameter (17). In that case, Fig. 8 show behavior of Hubble expansion parameter with time. we can see that the Hubble parameter in decreasing function of time. These plots
suggest the following form of $H$,

$$H = H_0 - Ct(1 + t),$$  \hspace{1cm} (23)

where $C$ is a positive constant.

Therefore, we can see typical behavior of the deceleration parameter in Fig. 9. It increased at the early universe to the phase where universe is accelerated, then it decreased and changes the sign to the deceleration epoch. Finally it yields to -1 in agreement with ΛCDM model.

In the plots of Fig. 10 we draw EoS parameter against time. The first plot shows that variation of $\alpha$ is not important and $\omega$ has not important variation in presence of higher order terms. The second plot shows variation with the constant $B$. For the cases of $B < 3$ the EoS parameter is decreasing function of time which yields to -1, while for the cases of $B \geq 3$ the EoS parameter is increasing function of time which yields to -1. The third plot shows that increasing $n$ decreases value of $\omega$. These plots obtained for $m = 3$. However, the last plot contains 5 curves corresponding to $m = 1, \ldots, 5$. The case of $m = 1$ which is corresponding to modified Chaplygin gas illustrated by violet line.

In the plots of Fig. 11 we can see evolution of $\dot{G} / G$ in agreement with observational data.

5 Statefinder diagnostics

In the framework of general relativity, dark energy can explain the present cosmic acceleration. Except cosmological constant there are many others candidates of dark energy (quintom, quintessence, brane, modified
gravity etc.) are proposed. The property of dark energy is model dependent and to differentiate different models of dark energy, a sensitive diagnostic tool is needed. Hubble parameter $H$ and deceleration parameter $q$ are very important quantities which can describe the geometric properties of the universe. Since $\ddot{a} > 0$, hence $H > 0$ means the expansion of the universe. Also, $\dddot{a} > 0$, which is $q < 0$ indicates the accelerated expansion of the universe. Since, the various dark energy models give $H > 0$ and $q < 0$, they can not provide enough evidence to differentiate the more accurate cosmological observational data and the more general models of dark energy. For this aim, we need higher order of time derivative of scale factor and geometrical tool. Sahni et.al [43] proposed geometrical statefinder diagnostic tool, based on dimensionless parameters $(r, s)$ which are function of scale factor and its time derivative. These parameters are defined as the follows,

$$r = \frac{1}{H^3} \frac{\ddot{a}}{a} \quad s = \frac{r - 1}{3(q - \frac{1}{2})}.$$  \hspace{1cm} (24)

Plots of Fig. 12 show results of our numerical analysis in both models for the cases of constant $(G, \Lambda)$, and varying $(G, \Lambda)$. We can see that the value of $r$ in the cases of varying $G$ and $\Lambda$ are lower than the cases of constant $G$ and $\Lambda$. However $(r, s) = (1, 0)$ verified in all cases.
In this work we considered higher order $f(R)$ gravity with varying $G$ and $\Lambda$. We assumed Chaplygin gas as dark energy and considered two models to describe evolution of the universe. First model was variable modified Chaplygin gas model (VMCG). The constant $B$ in ordinary MCG in no longer constant in VMCG and varies with time. The second model was extended Chaplygin gas. This is indeed extended version of MCG to recover higher order barotropic fluid EoS.

We assumed $\Lambda$ proportional to the energy density and analyzed some important cosmological parameters such as Hubble expansion, deceleration and EoS parameters. We found that the cases of varying $G$ and $\Lambda$ have more agreement with observational data comparing with the cases of constant $G$ and $\Lambda$.

Also we found that the extended Chaplygin gas model is more appropriate model than the variable modified Chaplygin gas model. We can see also acceleration to deceleration phase transition in the extended Chaplygin gas model.

In summary we propose higher order corrected extended Chaplygin gas with varying $G$ and $\Lambda$ as a model to describe universe.

6 Conclusion

In this work we considered higher order $f(R)$ gravity with varying $G$ and $\Lambda$. We assumed Chaplygin gas as dark energy and considered two models to describe evolution of the universe. First model was variable modified Chaplygin gas model (VMCG). The constant $B$ in ordinary MCG in no longer constant in VMCG and varies with time. The second model was extended Chaplygin gas. This is indeed extended version of MCG to recover higher order barotropic fluid EoS.

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Figure 12: $r - s$. Top panels corresponds to the cases of constant $G$ and $\Lambda$ for model 1 and model 2, respectively. Bottom panels corresponds to the cases of varying $G$ and $\Lambda$ for model 1 and model 2, respectively.

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