Cosmography of Generalized Ghost Dark Energy Model in \( f(G) \) Gravity\(^1 \)

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Abstract—This paper is devoted to construction of generalized ghost dark energy \( f(G) \) model by using correspondence scheme for both interacting and noninteracting scenarios with pressureless matter and power-law scale factor. We study the cosmological implications of the resulting model through equation of state parameter and \( \omega_{\text{DE}}-\rho_{\text{DE}} \) as well as \( r-s \) plane. We also discuss stability of the resulting model through squared speed of sound parameter. The equation of state parameter represents phantom phase of the Universe for both cases while the squared speed of sound indicates stability of this model. The \( \omega_{\text{DE}}-\rho_{\text{DE}} \) plane represents thawing region whereas \( r-s \) plane corresponds to phantom and quintessence DE regimes for both interacting and noninteracting cases.

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1. INTRODUCTION

Current cosmic expansion has been supported by several observational evidences, i.e., supernova type Ia, cosmic microwave background radiation, large scale structure etc. This expanding picture of the universe is the outcome of exotic force exerting large negative pressure, known as dark energy (DE). Many DE models have been suggested to interpret DE phenomena and cosmic evolution. There are mainly two approaches to study the nature of DE: dynamical DE models and modified theories of gravity.

A dynamical DE model known as Veneziano ghost dark energy (GDE) [1] has nontrivial physical properties of cosmos. This model is assumed to resolve \( U(1) \) problem [2] using low energy theory of quantum chromodynamics (QCD). The GDE offers nothing to the vacuum energy density in Minkowski spacetime but in curved spacetime it uplifts small vacuum energy density proportional to \( \Lambda_{\text{QCD}}^3 H \), where \( \Lambda_{\text{QCD}} \) and \( H \) are QCD mass scale and Hubble parameter, respectively [3]. Taking \( \Lambda_{\text{QCD}} \approx 100 \text{ MeV} \) and \( H \approx 10^{-33} \text{ MeV of present time} \), it follows that \( \Lambda_{\text{QCD}}^3 H \) gives right order \((10^{-3})^4 \text{ eV} \) of the observed GDE density. This small value amazingly provides the required exotic force to the accelerating universe as well as get rid from the fine tuning problem. The energy density of GDE is expressed as [4]

\[ \rho_{\text{GDE}} = \alpha H, \]

where \( \alpha \) is an arbitrary constant having dimension [\text{energy}]^3.

The characteristics of zero point fluctuation of quantum field in total energy density need to calculated by deducting the Minkowski spacetime results from the estimated values of FRW spacetime [5]. The deviation \( \Lambda_{\text{QCD}}^2 H^2 \) (appeared in vacuum energy density of these spaces) is taken in the renormalization of Newton constant \( G \), where \( \Lambda_c \) is UV cutoff. This fact holds under the assumption that the conservation of vacuum expectation value of the energy—momentum tensor exists in isolation. Zhitnitsky [6] found that Veneziano GDE is not merely of order of \( H \), a term \( H^2 \) must be added using the fact in [5]. The vacuum energy of ghost field has the form \( H + O(H^2) \), where the term \( H^2 \) of GDE model explains the early cosmic expansion. The inclusion of second term in GDE gives consistency results with observational data [7]. The energy density of generalized ghost dark energy (GGDE) can be defined as

\[ \rho_{\text{GGDE}} = \alpha H + \beta H^2, \]

where \( \beta \) is an arbitrary constant having dimension [\text{energy}]^2.

Khodam et al. [8] studied the reconstruction of \( f(R, T) \) gravity for GGDE model and discussed cosmic evolution through cosmological parameters. Ebrahimi et al. [9] analyzed the interacting GGDE in non-flat
universe and found that the EoS parameter lies in the phantom era of the universe. Malekjani [10] discussed the cosmography of GGDE and found that this model is closer to observational data. Pasqua et al. [11] explored DE with higher order of \( H \) in \( f(R, T) \) gravity and found that the model is classically stable in the early universe while unstable for the current era. Chatto- padhyay [12] reconstructed QCD ghost \( f(T) \) model to analyze current cosmic evolution and its consequences which gives phantom and quintessence regime of cosmos. Borah and Ansari [13] analyzed the cosmography of GGDE and found that this model is classically stable in the phantom era of the universe. Malekjani [10] discussed DE model in modified GB gravity to explain current cosmic evolution and also alleviated the issues of hierarchy problem. De Felice and Tsujikawa [16] explored the consistency of \( f(G) \) model using solar system constraints. In [17], the \( f(G, T) \) model of a pilgrim DE was constructed using the corresponding scenario; for \( u < 0 \) (\( u \) is the pilgrim parameter), the phantom-like Universe was obtained.

In this paper, we use correspondence scheme for reconstructing GGDE \( f(G) \) model in both interaction as well as non-interaction scenario. We study cosmic evolution through EoS parameter, squared speed of sound parameter and phase planes. The paper is organized as follows. In the next section, we briefly discuss \( f(G) \) gravity and construct GGDE \( f(G) \) model through reconstruction scheme. Section 3 is devoted to study the evolution of GGDE model through cosmological parameters for noninteracting case while Section 4 studies the interacting case. Finally, we discuss our results in the last section.

2. RECONSTRUCTION OF GGDE \( f(G) \) MODEL

In this section, we apply a correspondence scheme between GGDE and \( f(G) \) gravity to reconstruct GGDE \( f(G) \) model. The action of \( f(G) \) gravity is defined as [17]

\[
S = \int d^4x\sqrt{-g}\left(\frac{R}{2\kappa} + f(G) + \mathcal{L}_m\right),
\]

(2)

where \( \kappa = 1 \) and \( \mathcal{L}_m \) are the coupling constant and matter Lagrangian density, respectively. The corresponding field equations are

\[
R_{\alpha\beta} - \frac{1}{2} R g_{\alpha\beta} = T_{\alpha\beta}^{\text{eff}},
\]

(3)

\( T_{\alpha\beta}^{\text{eff}} \) is the effective energy–momentum tensor given by

\[
T_{\alpha\beta}^{\text{eff}} = \kappa^2 R_{\alpha\beta}^{(m)} - \delta R_{\alpha\beta\gamma} + R^{\gamma}_{\beta\gamma} g_{\alpha\beta} + R_{\gamma\beta} g_{\alpha\gamma} - R_{\alpha\beta} g^{\gamma\delta} g_{\gamma\delta}
\]

(4)

\[
+ \frac{1}{2} R (g_{\alpha\beta} g_{\gamma\delta} - g_{\alpha\gamma} g_{\beta\delta}) \nabla^{\gamma} \nabla^{\delta} g_{\alpha\beta} - (G f - f) g_{\alpha\beta},
\]

here \( f_G = \frac{df}{df_G} \). \n\( V_\alpha \) and \( T_{\alpha\beta}^{(m)} \) represent the covariant derivative and matter energy–momentum tensor, respectively.

The field equations for FRW universe model in the presence of perfect fluid take the form

\[
3H^2 = \rho_m + \rho_{DE}, \quad -(2\dot{H} + 3H^2) = P_m + P_{DE},
\]

(5)

where \( \dot{H} \) represents time derivative and subscripts \( m \) denotes the matter contribution to energy density as well as pressure. The energy density and pressure of dark source terms are

\[
\rho_{DE} = \frac{1}{2} (G f - f - 24 H^2 (2 H^2 + 3H^2 + 4H^2 H') f_{GG}),
\]

(6)

\[
P_{DE} = \frac{1}{2} (8H^2 f_G + 16H (H^2 + H') f'_G - G f_G + f'),
\]

(7)

where \( G = 24H^2 (H^2 + H') \). The first field equation leads to

\[
\Omega_m + \Omega_{DE} = 1,
\]

(8)

where \( \Omega_m = \frac{\rho_m}{3H^2} \) and \( \Omega_{DE} = \frac{\rho_{DE}}{3H^2} \) are the fractional energy densities associated with matter and dark source, respectively.

We take the correspondence between GGDE and \( f(G) \) model by equating their densities, i.e., \( \rho_{DE} = \rho_{GGDE} \). Using Eqs. (1) and (6), it follows that

\[
G f_G - f - 24 H^2 (2 H^2 + 3H^2 + 4H^2 H') f_{GG} = 2 \alpha H + 2 \beta H^2.
\]

(9)

We choose the power-law form of the scale factor as

\[
a(t) = a_0 t^m,
\]

(10)

where \( a_0 \) is a constant representing the present day value of the scale factor. Using Eq. (10) in (9), we obtain

\[
G^2 f_{GG} + m - \frac{1}{4} f G^2 - m - \frac{1}{4} f = \frac{\alpha m^4 (m - 1)^4 G^4}{2^7 3^4} + \frac{\beta m^3 (m - 1) \sqrt{G}}{2^3}.
\]

(11)
This is a second order linear differential equation having solution of the form

\[ f(G) = c_1 G^{(1-m)} + c_2 G \]

where \( c_1 \) and \( c_2 \) are integration constants. This represents the reconstructed GGDE \( f(G) \) model. Using Eq. (12) in (6) and (7), we have

\[ \rho_{DE} = \frac{\alpha m^2 G^4}{2^3 3^3 (m-1)^3} + \beta \frac{6 m G}{m(m+1)}, \]

\[ P_{DE} = \frac{\alpha G^2 (1 - 3 m)}{2^3 3^3 m^3 (m-1)^4} - \frac{\beta(3m-2)}{3 \frac{2^3 3^2}{2^3 3^2}} \sqrt{\frac{G}{m(m-1)}}, \]

where \( m \neq 1 \).

The graphical analysis of reconstructed GGDE \( f(G) \) model against \( G \) is shown in Fig. 1. We take \( c_1 = -0.5, c_2 = -1.25, \alpha = -8.01 \) throughout the analysis. It is observed that the reconstructed \( f(G) \) model initially exhibits rapid increase and then gradually declines as \( G \) increases in the range \( 2 \leq m \leq 4 \). It is observed that \( f(G) \) remains positive over the interval \( 0.01 \leq G \leq 1.6 \) whereas it undergoes large negative values for \( G > 1.6 \). Moreover, our reconstructed model \( f(G) \rightarrow 0 \) as \( G \rightarrow 0 \) which demonstrates a realistic features of the model.

3. NONINTERACTING GGDE \( f(G) \) MODEL

Here, we consider the dust case, i.e., \( (P_m = 0) \) where CDM does not interact with GGDE. In this case, the conservation equations for matter and dark source terms take the form

\[ \dot{\rho}_m + 3H \rho_m = 0, \]

\[ \dot{\rho}_{DE} + 3H \rho_{DE}(1 + \omega_{DE}) = 0. \]

The solution of Eq. (15) gives

\[ \rho_m = \rho_m a^{-3}, \]

where \( \rho_m \) is an arbitrary constant.

Now we investigate the behavior of EoS parameter, squared speed of sound and cosmological planes for GGDE \( f(G) \) model.

3.1. EoS Parameter

The EoS parameter is given by

\[ \omega_{DE} = \frac{P_{DE}}{\rho_{DE}}. \]

Substituting Eqs. (13) and (14) in (18), it follows that

\[ \omega_{DE} = \frac{\alpha(1 - 3 m) - \beta(3m-2)m}{3m(\alpha + \beta m)}. \]

The plot of EoS parameter is shown in Fig. 2 for \( 2 \leq m \leq 4 \). This represents phantom era of the universe and crosses the phantom divide line at cosmic time \( t = 4.5 \). Moreover, it is observed that the universe converges in quintessence epoch for late cosmic evolutionary
regime. This indicates that the universe is approaching towards less accelerated era for late-time evolutionary regime.

### 3.2. Squared Speed of Sound Parameter

The squared speed of sound parameter is

\[ v_s^2 = \frac{\dot{p}_{DE}}{\dot{\rho}_{DE}}. \] (20)

The signature of \( v_s^2 \) plays a vital role to discuss stability of the reconstructed GGDE model. The positive sign of \( v_s^2 \) represents stability whereas its negative sign shows instability of the model. Using Eqs. (13) and (14) in (20), we have

\[ v_s^2 = \frac{\alpha(1-3m)t - 2\beta m(3m-2)m}{3m(\alpha t + 2\beta m)}. \]

Figure 3 shows graphical description of the squared speed of sound for the range \( 4 > m > 2 \). It is seen that GGDE \( f(G) \) model is stable as \( v_s^2 > 0 \) over the range \( 3.4 < t < 4.5 \).

### 3.3. The \( \omega_{DE} - \omega'_{DE} \) Plane

Caldwell and Linder [18] suggested \( \omega_{DE} - \omega'_{DE} \) plane in order to check the response of quintessence DE model. They describe the plane into two parts, thawing (\( \omega_{DE} < 0, \omega'_{DE} > 0 \)) and freezing regions (\( \omega_{DE} < 0, \omega'_{DE} < 0 \)).

Using Eq. (19), it follows that

\[ \omega'_{DE} = \frac{\alpha t(1-3m)}{3m^2(\alpha t + \beta m)} - \frac{\alpha t(\alpha(1-3m)t - \beta(3m-2)m)}{3m^2(\alpha t + \beta m)}. \]

The graphical description of \( \omega_{DE} - \omega'_{DE} \) plane is exhibited in Fig. 4 for three particular values of \( m \), i.e., \( m = 2, 2.1, \) and \( 2.2 \). It is observed that \( \omega_{DE} - \omega'_{DE} \) Plane represents thawing region for distinct values of \( m \) showing a consistent trend with our expanding universe. This represents that our derived model is in less accelerating phase as compared with freezing region.

### 3.4. The \( r-s \) Plane

Sahni et al. [19] introduced two dimensionless parameters known as statefinders and expressed as

\[ r = \frac{\ddot{a}}{aH}, \quad s = \frac{r - 1}{3(q - \frac{1}{2})}. \] (21)

The parameter \( r \) can also be written in the form of deceleration parameter

\[ r = 2q^2 + q - \ddot{q}. \] (22)

These statefinders are useful in providing the distance of specific DE model using \( \Lambda \)CDM limit and also helpful to classify different DE models. It is well-known that \((r, s) = (1, 0)\) stands for CDM limit and \((r, s) = (1, 1)\) for \( \Lambda \)CDM limit. Furthermore, \((r < 1, s > 0)\) region gives the phantom and quintessence DE regimes whereas \((s < 0, r > 1)\) region interprets Chaplygin gas model. Using Eq. (19) in (21) and (22), we have

\[
0 = \frac{1}{2m^2(\alpha t + \beta m)}[(\alpha t)^2(1-3m+2m^2)
+ 2\beta^2 m^2(2m^2-3m+2) + \alpha \beta m
\times (m + t(4m^2 - 9m + 4))],
\]
Figure 5 shows the plot of $r - s$ plane for reconstructed GGDE $f(G)$ model with $m = 2, 2.1,$ and $2.2$. These trajectories indicate that the $r - s$ plane leads to phantom and quintessence DE era for three specific values of $m$ whereas both CDM and $\Lambda$CDM limit cannot be achieved for our reconstructed model.

4. INTERACTING GGDE $f(G)$ MODEL

In this case, GGDE and pressureless CDM violate the conservation equation given as

$$\dot{\rho}_m + 3H\rho_m = \Upsilon,$$

$$\dot{\rho}_{DE} + 3H\rho_{DE}(1 + \omega_{DE}) = -\Upsilon,$$

where $\Upsilon$ represents the interaction that exchanges energy between CDM and GGDE. This interaction term has many simple forms like $3d_1H\rho_{DE}$, $3d_2H\rho_m$, and $3d_3H(\rho_{DE} + \rho_m)$. $d_i$ is the coupling constant. Cai and Su [20] found that interaction necessarily changes its signature from deceleration to acceleration for describing the cosmic evolution. These three choices of interaction disobey the conditions for evolving the universe. Hence, we take interaction as [21]

$$\Upsilon = 3d_iH(\rho_{DE} - \rho_m),$$

which changes its signature while interpreting the universe and evolves from deceleration to acceleration. Here, we discuss some cosmological parameters of reconstructed GGDE $f(G)$ model in this scenario.

The corresponding EoS parameter is given by

$$\omega_{DE} = \frac{\alpha(1 - 3m)t - \beta(3m - 2)m}{3m(\alpha t + \beta m)} - d\left(2 - \frac{2}{\alpha t + \beta m} + \frac{1}{3m(\alpha t + \beta m)}\right) \times (\alpha(1 - 3m)t - \beta(3m - 2)m).$$

Figure 6 represents the graphical description of EoS parameter for $3 \leq m \leq 4$ which shows phantom phase of the universe and approaches to phantom divide line but never cross it for $m \geq 3$ as $t$ increases. It is observed that it crosses the phantom divide line $\omega_{DE} = -1$ somewhere in early cosmic time while accelerated in quintessence region. Moreover, our phantom-like universe has a tendency to converge into big-rip for late-time cosmic evolution or may manifest the ultimate fate as the same acceleration paradigm through which it is currently undergoing.

The resulting squared speed of sound is

$$v_s^2 = \frac{-1}{3m(\alpha t + 2\beta m)}(3am(1 + d) + \alpha t(d - 1)) + 6\beta m^2(1 + d) - 4m\beta(d - 1) - 12md).$$
We plot the squared speed of sound for the range \(3 \leq m \leq 4\) as shown in Fig. 7 which shows that \(v^2_c > 0\) for coupling constant \(d = 0.25\) leading to the stable GGDE \(f(G)\) model for \(3.57 < t < 3.92\). The evolutionary of \(\omega_{DE}\) is

\[
\omega_{DE} = \frac{-\alpha(\beta + d(6 - \beta))}{m(\alpha + \beta m)^2}.
\]

Figure 8 illustrates this plane with three distinct values of \(m\), i.e., \(m = 3, 3.4,\) and 3.8. It is found that \(\omega_{DE} - \omega_{DE}'\) plane corresponds to thawing region for these choices of \(m\), showing a consistent behavior with the expanding universe.

The \(r - s\) plane becomes

\[
r = 2 \left( \frac{1}{2} + \frac{\alpha(1 - 3m)t - \beta m(3m - 2)}{2m(\alpha + \beta m)} \right)
- \frac{3d}{2} \left( 2 - \frac{2}{\alpha + \beta m} + \frac{1}{3m(\alpha + \beta m)} \times (\alpha(1 - 3m)t - \beta m(3m - 2)) \right) \right)^2
\]

\[
+ \frac{1}{2} + \frac{\alpha(1 - 3m)t - \beta m(3m - 2)}{2m(\alpha + \beta m)}
- \frac{3d}{2} \left( 2 - \frac{2}{\alpha + \beta m} + \frac{1}{3m(\alpha + \beta m)} \times \frac{\alpha(1 - 3m)t - \beta m(3m - 2)}{\alpha(1 - 3m)t - \beta m(3m - 2)} \right) \right)^2
\]

\[
- \frac{\alpha(1 - 3m)}{2m(\alpha + \beta m)} + \frac{1}{2m}
\times \frac{\alpha}{(\alpha + \beta m)} (\alpha(1 - 3m)t - \beta m(3m - 2))^2
\]

\[
+ \frac{3d}{2} \left( \frac{2\alpha}{(\alpha + \beta m)^2} + \frac{\alpha(1 - 3m)}{3m(\alpha + \beta m)} \right)
- \frac{\alpha(1 - 3m)t - \beta m(3m - 2)}{3m(\alpha + \beta m)^2}
\times \frac{\alpha(1 - 3m)t - \beta m(3m - 2)}{2m(\alpha + \beta m)}
\]

\[
- \frac{3d}{2} \left( \frac{2\alpha}{(\alpha + \beta m)^2} + \frac{\alpha(1 - 3m)t - \beta m(3m - 2)}{3m(\alpha + \beta m)^2} \right).
\]

The trajectories of \(r - s\) plane for GGDE \(f(G)\) model with \(m = 3, 3.4,\) and 3.8 are shown in Fig. 9. These trajectories show that the \(r - s\) plane leads to the phantom region for major portion while Chaplygin gas model regimes over a small range for these choices of \(m\) using \(d = 0.25\). Also CDM limit is achieved for our reconstructed \(f(G)\) model in the context of interacting scenario.
5. CONCLUDING REMARKS

In this paper, we have used reconstruction technique of GGDE $f(G)$ model with power-law form of the scale factor. We have analyzed the graphical behavior of our reconstructed model by assuming GGDE parameters $\alpha = -8.05$ and $\beta = 7.51$ for non-interacting and $\beta = 4.51$ for interacting scenario. The summary of the results is given as follows.

- The reconstructed GGDE $f(G)$ model (Fig. 1) represents rapid increase initially and then it attains decreasing pattern forever. This indicates the realistic behavior of our model.
- The EoS parameter (Fig. 2) exhibits transition from phantom to quintessence regimes for noninteracting case whereas (Fig. 5) indicates phantom era of the universe for interacting scenario. In the nutshell, GGDE $f(G)$ model supports the DE phenomenon.
- The squared speed of sound parameter (Figs. 3 and 7) represents stability of our reconstructed GGDE model for specific range of cosmic time in the interval $2 \leq m \leq 4$ and $3 \leq m \leq 4$, respectively.
- The trajectories of the $\omega_{DE} - \omega_{DE}$ plane (Fig. 4) for $m = 2$, 2.1, and 2.2 in non-interaction while (Fig. 8) $m = 3$, 3.4 and 3.8 in interaction case gives the thawing region, respectively.
- The evolutionary behavior of the $r - s$ plane (Figs. 5 and 9) provides the phantom and quintessence DE regimes for these values of $m$. Furthermore, CDM limit is achieved through interacting scenario while $\Lambda$CDM limit cannot be attained in both cases of our model.

We conclude that the GGDE $f(G)$ model represents stable characteristics as well as consistent behavior with current accelerated expanding paradigm of the universe for appropriate choice of GGDE parameters. It is observed that the phantom-like behavior of cosmos predicts more accelerated regime which may give big-rip or current accelerated status as an ultimate fate of the universe. We have found that the inclusion of interaction regime between DE and dark matter yields phantom-like universe as observed by pilgrim dark energy models. We have also noticed that EoS parameter shows consistency with the current observational data [23] given as

$$\omega_{DE} = -1.023^{+0.091}_{-0.096} (\text{PlanckTT + LowP + ext}),$$

$$\omega_{DE} = -1.006^{+0.085}_{-0.091} (\text{PlanckTT + LowP + lensing + ext}),$$

$$\omega_{DE} = -1.019^{+0.076}_{-0.080} (\text{PlanckTT, TE, EE + LowP + ext}).$$

These values have been obtained by implementing various observational techniques at 95% confidence level. It is worth mentioning here that our results are consistent with those obtained for reconstructed QCD ghost $f(T)$ model [12] as well as $f(R, T)$ model [22].

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