Non-minimal Maxwell-Modified Gauss-Bonnet Cosmologies: Inflation and Dark Energy

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Abstract

In this paper we show that power-law inflation can be realized in non-minimal gravitational coupling of electromagnetic field with a general function of Gauss-Bonnet invariant. Such a non-minimal coupling may appear due to quantum corrections. We also consider modified Maxwell-\(F(G)\) gravity in which non-minimal coupling between electromagnetic field and \(f(G)\) occur in the framework of modified Gauss-Bonnet gravity. It is shown that inflationary cosmology and late-time accelerated expansion of the universe are possible in such a theory.

Keywords: Inflation; Late-time acceleration; Non-minimal coupling; Gauss-Bonnet gravity.

1 Introduction

Cosmological observations indicate that there are two periods of accelerated expansion in our universe: cosmic inflation in the early universe and acceleration in the current expansion of the universe [1-4].

In order to explain the late-time acceleration of the universe, one needs to introduce a negative pressure component which is called dark energy (DE). In this direction we can consider field models of dark energy. The field models that have been discussed widely in the literature consider a cosmological constant [5], a canonical scalar field (quintessence) [6], a

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phantom field, that is a scalar field with a negative sign of the kinetic term \[7, 8\], or the combination of quintessence and phantom in a unified model named quintom \[9\].

An alternative approach to explain DE is the modification of general relativity (GR) \[10, 11, 12, 13, 14, 15\], and in the simplest way adding an arbitrary function of Ricci scalar to the Einstein-Hilbert action, what is well known as \(f(R)\) gravity \[16, 17\].

Another modification of GR is modified Gauss-Bonnet gravity \[15\], which is obtain by inserting a general function of Gauss-Bonnet invariant, \(f(G)\), in the GR action.

In the other side non-minimal coupling between the Ricci scalar and matter Lagrangian can be seen as the source of inflation and current acceleration expansion of the universe \[19, 20\]. Such a non-minimal coupling between \(f(R)/f(G)\) gravity and kinetic part of Lagrangian of a massless scalar field has been investigated in Ref. \[21\]. Non-minimal coupling of a viable \(f(R)\) gravity with electromagnetism Lagrangian and cosmological consequences of this model about inflation and late-time acceleration has been considered in \[22\]. Also cosmology in non-minimal non-Abelian gauge theory (Yang-Mills theory), in which the non-Abelian gauge field couples to \(f(R)\) gravity has been explored in Ref. \[23\]. Furthermore, it is shown that both inflation and late time accelerated expansion of the universe can be realized in non-minimal vector model in the framework of modified gravity \[23\]. In addition, the conditions for the non-minimal gravitational coupling of electromagnetic field in order that finite-time singularities can not appear have been investigated in Ref. \[24\]. Ref. \[25\], has been considered \(F(R)\) gravity coupled to non-linear electrodynamics. The criteria for the validity of non-minimal coupling between scalar curvature and matter Lagrangian have been studied in Refs. \[26, 27, 28\].

In the present work following the Ref. \[22\], we consider inflation and late time acceleration of the universe in non-minimal electromagnetism in which the electromagnetism Lagrangian couples to the arbitrary function of Gauss-Bonnet invariant, \(f(G)\). Additionally we use the procedure of Ref. \[29\] in analyzing the electromagnetism in large scales. We show that power-law inflation can be realized in non-minimally coupled electromagnetism Lagrangian with modified Gauss-Bonnet gravity in the framework of GR. Furthermore, we study inflation and late time accelerated expansion of the universe in non-minimal Maxwell-\(f(G)\) gravity in the framework of modified Gauss-Bonnet gravity. We use the proposal of Ref. \[30\], for a viable \(f(G)\) gravity and note that in \(f(G)\) gravity , there are no problems with the Newton law and instabilities \[31\].

An outline of this paper is as follows. In section 2 we examine power-law inflation in a non-minimally coupled Maxwell field with \(f(G)\) gravity in GR framework. In section 3 we show that both inflation and late-time cosmic acceleration can be realized in a model of non-minimal gravitational coupling of the Maxwell field in a modified Gauss-Bonnet gravity proposed in Ref. \[30\]. Section 4 is devoted to conclusion.

2 Power-law inflation in general relativity

We start with the following action:
Bonnet gravity. resent non-minimal coupling between electromagnetism Lagrangian and modified Gauss-Bonnet gravity. In a flat Friedmann-Robertson-Walker (FRW) space-time with the metric $ds^2 = -dt^2 + a^2(t)(dr^2 + r^2d\Omega^2),$ the components of Ricci tensor $R_{\mu\nu}$ and Ricci scalar $R,$ are given by

$$R_{00} = -3(\dot{H} + H^2), \quad R_{ij} = a^2(t)(\dot{H} + 3H^2)\delta_{ij}, \quad R = 6(\dot{H} + 2H^2),$$

where $H = \frac{\dot{a}(t)}{a(t)}$ is the Hubble parameter and $a(t)$ is the scale factor. Also Gauss-Bonnet invariant in this background is

$$G = 24(\dot{H}H^2 + H^4).$$

The $(0,0)$ component and sum of $(i, i)$ components of equation (3) in FRW space-time have the following forms respectively

$$H^2 = \frac{\kappa^2}{3} \left[ (1 + f(G)) \left( g^{\gamma\delta} F_{\gamma0} F_{\delta0} - \frac{1}{4} g_{00} F_{\gamma\delta} F^{\gamma\delta} \right) + 6 \left( f'(G) \left( \dot{H}H^2 + H^4 \right) \right) \right].$$
\[-24H^3(\dot{H}H^2 + 2H\dot{H}^2 + 4\dot{H}H^3) f''(G) F_{\gamma \delta} F^{\gamma \delta} - 6H^3 f'(G) \frac{\partial}{\partial t} (F_{\gamma \delta} F^{\gamma \delta})\],

(8)

and

\[2\dot{H} + 3H^2 = \kappa^2 \left[ \frac{1}{12} (1 + f(G)) F_{\gamma \delta} F^{\gamma \delta} + \left( 6f'(G)(\dot{H}H^2 + H^4) \right. \right. \]

\[-48 \left. \left. \left[ f''(G)(8\dot{H}\dot{H}H^3 + 6\dot{H}^3H^2 + 24\dot{H}^2H^4 + 6\ddot{H}H^5 + 8\dot{H}^2H^6 + \dddot{H}H^4) \right) F_{\gamma \delta} F^{\gamma \delta} - 4 \left[ f'(G)(H\dot{H} + H^3) \right. \right. \right. \]

\[+ 24f''(G)H^2(\dot{H}H^2 + 2H^2H^2 + 4\dot{H}H^3)^2 \right) F_{\gamma \delta} F^{\gamma \delta} - 4 \left. \left. \left. \left[ f'(G)H\dot{H} + H^3 \right) \right. \right. \right. \]

\[+ 24f''(G)(\dot{H}H^4 + 2H^2H^3 + 4\dot{H}H^5) \right] \frac{\partial}{\partial t} (F_{\gamma \delta} F^{\gamma \delta}) - 2f'(G)H^2 \frac{\partial^2}{\partial t^2} (F_{\gamma \delta} F^{\gamma \delta}) \right],

(9)

where we have neglected the second order spatial derivative of the quadratic quantity \(F_{\gamma \delta} F^{\gamma \delta}\). Now we are going to use the following relations \[22\],

\[g_{\gamma \delta} F_{0\gamma} F_{0\delta} - \frac{1}{4}g_{00} F_{\gamma \delta} F^{\gamma \delta} = \frac{1}{2} \left( |E_i(t, \vec{x})|^2 + |B_i(t, \vec{x})|^2 \right), \]

(10)

\[F_{\gamma \delta} F^{\gamma \delta} = 2 \left( |B_i(t, \vec{x})|^2 - |E_i(t, \vec{x})|^2 \right). \]

(11)

Here \(E_i(t, \vec{x})\) and \(B_i(t, \vec{x})\) are proper electric and magnetic fields respectively. The amplitude of the proper electric and magnetic fields on a comoving scale \(L = \frac{2\pi}{k}\) with the comoving wave number \(k\), are given by

\[|E_i(t)|^2 = \frac{|E_0|^2}{|(1 + f(G))|^2 a^4}, \quad |B_i(t)|^2 = \frac{|B_0|^2}{a^4}, \]

(12)

where \(|E_0|\) and \(|B_0|\) are constants. Furthermore, using (12) in (11), one obtains

\[\frac{\partial}{\partial t} (F_{\gamma \delta} F^{\gamma \delta}) = 8 \left\{ -H|B_i(t)|^2 + \left[ H + 12f'(G) \frac{\dot{H}H^2 + 2H^2H + 4\dot{H}H^3}{1 + f(G)} \right] |E_i(t)|^2 \right\}. \]

(13)

Because our interest is the generation of large scale magnetic fields instead of electric fields, we neglect terms in electric fields from this point. In this case substituting (12) and (13) in (8) and (9) lead to

\[H^2 = \kappa^2 \left[ \frac{1}{6} (1 + f(G)) + 2f'(G)(\dot{H}H^2 + 9H^4) \right. \]

\[\left. - 48(\dddot{H}H^5 + 2H^4\dot{H}^2 + 4H^6\dot{H}) f''(G) \right] \frac{|B_0|^2}{a^4}, \]

(14)
and
\[ 2\dot{H} + 3H^2 = \kappa^2 \left[ \frac{1}{6} (1 + f(G)) + 20 f'(G)(3\dot{H}H^2 - H^4) \right. \]
\[ + 48 f''(G)(-8\ddot{H}H^3 - 6\dot{H}^3H^2 + 8\dot{H}^2H^4 + 10\dot{H}H^5 - 8\dot{H}^2H^6 + 64\dot{H}H^6 - \ddot{H}H^4) \]
\[ \left. + 24 f'''(G)H^2(\ddot{H}^2 + 2\dot{H}^2 + 4\dot{H}H^3)^2 \right] \frac{|B_0|^2}{a^4}. \] (15)

respectively, where we have used \( \frac{\partial}{\partial t}(F_{\gamma\delta}F^{\gamma\delta}) \approx -8\dot{H}|B_i(t)|^2 + 32H^2|B_i(t)|^2 \).

From equations (14) and (15), we have
\[ \dot{H} + H^2 = \kappa^2 \left[ f'(G)(29\dot{H}H^2 - H^4) \right. \]
\[ + 24 f''(G)(-8\dot{H}H^3 - 6\dot{H}^3H^2 + 10\dot{H}^2H^4 + 11\dot{H}H^5 - 8\dot{H}^2H^6 + 68\dot{H}H^6 - \ddot{H}H^4) \]
\[ \left. + 12 f'''(G)H^2(\ddot{H}^2 + 2\dot{H}^2 + 4\dot{H}H^3)^2 \right] \frac{|B_0|^2}{a^4}. \] (16)

We examine the following function for \( f(G) \) which has been proposed in Ref. [32] as a realistic case for both inflation and late-time acceleration,
\[ f(G) = \frac{G^n}{c_1G^n + c_2} \] (17)

where \( c_1 \) and \( c_2 \) are constants and \( n \) is a positive integer.

For exploring power-law inflation, we assume \( a = a_0t^{h_0} \), therefore
\[ H = \frac{h_0}{t}, \quad \dot{H} = -\frac{h_0}{t^2}, \quad \ddot{H} = \frac{2h_0}{t^3}, \quad \dot{\ddot{H}} = -\frac{6h_0}{t^4}. \] (18)

Also we use the following approximate relations which satisfy at the inflationary period
\[ f(G) \approx \frac{1}{c_1} \left( 1 - \frac{c_2}{c_1}G^{-n} \right), \] (19)
\[ f'(G) \approx \frac{n c_2}{c_1} G^{-(n+1)}, \] (20)
\[ f''(G) \approx -\frac{n(n+1)c_2}{c_1} G^{-(n+2)}, \] (21)
\[ f'''(G) \approx \frac{n(n+1)(n+2)c_2}{c_1} G^{-(n+3)}. \] (22)

By substituting above approximate relations for \( f(G) \) and its derivatives and (18) in (16), one can obtain
\[ h_0 = \frac{2n + 1}{2}. \] (23)

If \( n \gg 1 \), \( h_0 \) becomes much larger than unity and power-law inflation can occur. Therefore, non-minimally coupled electromagnetic field with \( f(G) \) gravity can be a source of inflation.
This result is the same as in non-minimally coupled Maxwell field with $f(R)$ gravity \[22\]. We note that, in this paper we considered only the case in which the values of the terms proportional to $f'(G)$, $f''(G)$ and $f'''(G)$ in equations (14) and (15) are dominant to the values of the term proportional to $(1 + f(G))$. Because in the opposite case i.e. if the term proportional to $(1 + f(G))$ is dominant to the other terms, the power-low inflation can not be realized.

### 3 Inflation and late-time acceleration in modified Gauss-Bonnet gravity

Now, we consider a non-minimally coupled electromagnetic field in a modified Gauss-Bonnet gravity proposed in Ref. \[30\].

We describe the model by the following action

$$S = \int d^4x \sqrt{-g} \left[ \frac{1}{2\kappa^2} (R + F(G)) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} f(G) F_{\mu\nu} F^{\mu\nu} \right].$$  \hfill (24)

We note that in this case $F(G)$ is the modified part of gravity and it is different from the $f(G)$ in the last term in action (1). By choosing FRW metric (5), the $(0, 0)$ component and sum of $(i, i)$ components of equation of motion for $g_{\mu\nu}$, have the following forms

$$H^2 - \frac{1}{6} (G F'(G) - F(G)) + 4H^3 \dot{G} F''(G) = \frac{\kappa^2}{3} T_{00}^{eff}, \hfill (25)$$

and

$$2\dot{H} + 3H^2 + \frac{1}{2} (G F'(G) - F(G)) - 4H^2 (\dot{G} F''(G) + \dot{G}^2 F'''(G)) = -\kappa^2 T_{ii}^{eff}, \hfill (26)$$

where $T_{\mu\nu}^{eff}$ and $G$ are given by equations (4) and (7) respectively. As the previous section, we neglect the contribution of electric field and spatial derivatives of $F_{\mu\nu} F^{\mu\nu}$. Therefore, from equations (25) and (26), one can obtain

$$\begin{align*}
\dot{H} &+ H^2 + \frac{1}{3} (G F'(G) - F(G)) - 2H^2 (\dot{G} F''(G) + \dot{G}^2 F'''(G)) - 4H^3 \dot{G} F''(G) \\
&= \kappa^2 \left\{ f'(G) [29\dot{H} H^2 - H^4] + 24f''(G) [-8\ddot{H} H^3 - 6\dot{H}^2 H^2 + 10\dot{H}^2 H^4 + 11\ddot{H} H^5 \right. \\
&\left. - 8\dot{H}^2 H^6 + 68\dddot{H} H^6 - \dddot{H} H^4] + 12f'''(G) H^2 (\dddot{H} H^2 + 2\ddot{H}^2 H + 4\dot{H}^2 H^3) \right\} \frac{|B_0|^2}{a^4}. \hfill (27)\end{align*}$$

Here, we take $F(G)$ from Ref. \[30\],

$$F(G) = \frac{(G - G_0)^{2n+1} + G_0^{2n+1}}{c_3 + c_4 ((G - G_0)^{2n+1} + G_0^{2n+1})}, \hfill (28)$$

where $c_3$, $c_4$ are constants and $n$ is a positive integer. $G_0$ corresponds to the present value of the Gauss-Bonnet invariant. Since $F'(G) = 0$ when $G = G_0$ and $G = \infty$, $F(G)$ can be
regarded as an effective cosmological constant. We may consider $F(\infty)$ as the cosmological constant for the inflationary stage and $F(G_0)$ as that at the present time

$$\lim_{G \to \infty} F(G) = \frac{1}{c_4} = \Lambda,$$

$$F(G_0) = \frac{G_0^{2n+1}}{c_3 + c_4 G_0^{2n+1}} = 2G_0.$$  \hspace{1cm} (29)

From the above equations, we find

$$c_3 = \frac{G_0^{2n}}{2} - \frac{G_0^{2n+1}}{\Lambda} \approx \frac{G_0^{2n}}{2}, \quad c_4 = \frac{1}{\Lambda},$$

because $\frac{G_0^{2n}}{\Lambda} \ll 1$.

Also, $f(G)$ is given by

$$f(G) = -\frac{(G - G_0)^{2m+1} + G_0^{2m+1}}{c_5 + c_6 ((G - G_0)^{2m+1} + G_0^{2m+1})},$$

where $c_5, c_6$ are constants and $m$ is a positive integer. For the inflationary epoch we can use the following approximate relations:

$$F(G) \approx \frac{1}{c_4} \left[ 1 - \frac{c_3}{c_4} (G)^{-(2n+1)} \right],$$

and

$$f(G) \approx -\frac{1}{c_6} \left[ 1 - \frac{c_5}{c_6} (G)^{-(2m+1)} \right].$$

Because $G \to \infty$ at the inflationary stage and also $\lim_{G \to \infty} F(G) = \Lambda$ and $\lim_{G \to \infty} f(G) = \text{const}$, Eqs. (27) are reduced to

$$\dot{H} + H^2 = \frac{\Lambda}{3}.$$  \hspace{1cm} (35)

It follows from above equation that

$$a(t) \propto \exp \left( \frac{\Lambda}{3} \right)^{1/2} t,$$

so that exponential inflation can be realized. Thus, we conclude that the terms in $F(G)$ on the left hand side of Eqs. (27) can be a source of inflation, in addition to $f(G)$ on the right hand side of Eqs. (27).

At the present time, because $G - G_0 \ll 1$, if $m > n$, $f(G)$ becomes constant more rapidly than $F(G)$ in the limit $G \to G_0$. For such a case, when $G \to G_0$ Eqs. (27) lead to

$$\dot{H} + H^2 = \frac{2G_0}{3}.$$  \hspace{1cm} (37)

Then, from this equation one can obtain

$$a(t) \propto \exp \left( \frac{2G_0}{3} \right)^{1/2} t,$$

so that the late time acceleration of the universe can be realized. Thus, these results are in agreement with the results of Ref. \[22\] where non-minimal Maxwell-F(R) gravity has been considered.
4 Conclusion

To summarize, the non-minimal gravitational coupling of electromagnetic field with Gauss-Bonnet invariant function, $f(G)$, has been considered in Friedmann-Robertson-Walker background metric. Such a non-minimal coupling has been examined in the framework of general relativity. We have shown that power-law inflation can be realized in this model which is described by action (1). We have also studied cosmology in non-minimally coupled electromagnetic field in the framework of modified Gauss-Bonnet gravity, $F(G)$. It has been shown that both inflation and late-time acceleration of the universe can be realized in such a model proposed in Ref. [30].

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