Anisotropic power-law inflation for a conformal-violating Maxwell model

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Abstract
A set of power-law solutions of a conformal-violating Maxwell model with a non-standard scalar-vector coupling will be shown in this paper. In particular, we are interested in a coupling term of the form $X^{2n} F_{\mu\nu} F_{\mu\nu}$ with $X$ denoting the kinetic term of the scalar field. Stability analysis indicates that the new set of anisotropic power-law solutions is unstable during the inflationary phase. The result is consistent with the cosmic no-hair conjecture. We show, however, that a set of stable slowly expanding solutions does exist for a small range of parameters $\lambda$ and $n$. Hence a small anisotropy can survive during the slowly expanding phase.

1 Introduction

The cosmic inflation [1–3] has been regarded as a main paradigm of the modern cosmology. It follows from the success of the cosmic inflation resolving quite a number of cosmological problems such as the horizon, flatness, and magnetic-monopole problems [1–3]. In addition, the standard inflation model with our early universe assumed to be homogeneous and isotropic has been important in realizing many cosmic microwave background (CMB) observation results including the Wilkinson Microwave Anisotropy Probe (WMAP) [4,5] and the Planck [6,7].

Some recent CMB anomalies was, however, found. For example the hemispherical asymmetry and the cold spot have been detected by the WMAP and Planck. Anisotropic models have therefore been considered as a generalization of the FLRW inflation [8]. Consequently, modifications for the FLRW inflation are also necessary in order to accommodate the nature of the observed anomalies of CMB. It turns out that one of the simplest modifications is by replacing the FLRW metric by anisotropic but homogeneous Bianchi type spacetimes [9,10]. Note that many predictions made with anisotropic inflation have been done before the mentioned anomalies were detected [11,12].

The Bianchi models have also been discussed extensively in providing evidences for the cosmic no-hair conjecture proposed by Hawking and his colleagues [13,14]. The cosmic no-hair conjecture postulates that the final-time state of our universe will be simply homogeneous and isotropic regardless of any initial conditions and states of the universe in early time [13,14]. This conjecture has been a great challenge to the physicists and cosmologists for several decades. Some partial proofs to this conjecture have been worked out. In particular, this conjecture has been theoretically proved for the Bianchi spaces by Wald with an energy conditions approach [15].

Recently, some people have tried to extend the Wald’s proof to a more general scenario, in which the spacetime of universe is assumed to be inhomogeneous [16,17]. Note that some other interesting proofs for this cosmic no-hair conjecture can be seen in Refs. [18–20]. Besides the theoretical approaches, a general test using Planck’s data on the CMB temperature and polarization has provided observational constraints on the isotropy of the universe [21], by which we might see how precise the cosmic no-hair conjecture is.

The validity of the cosmic no-hair conjecture has also been tested in various cosmological models, including the higher curvature models [22–28], the Lorentz Chern-Simons theory [29,30], the massive vector theories [31–34], the non-linear massive gravity models [35–39], the massive bigravity [40–42], and the supergravity-motivated models [43–78]. Among these models, an interesting counter-example to the cosmic no-hair conjecture arising in the supergravity-motivated model proposed by Kanno, Soda, and Watanabe (KSW) [43,44] has attracted many attentions [45–78].

As a result, the KSW model has been shown to admit a stable and attractive Bianchi type I inflationary solution [43,44] due to the existence of an unusual coupling term between
To generate non-trivial magnetic fields \([79–90]\). Indeed, the conformal invariance must be broken by the coupling between scalar and vector fields, \(\exp [2\phi] F_{\mu\nu} F^{\mu\nu}\).

Note that the KSW model can be regarded as a subclass of the conformal-violating Maxwell theory with an extended coupling term \(I(\phi, R, X, \ldots) F_{\mu\nu} F^{\mu\nu}\) [79–107]. Here \(I(\phi, R, X, \ldots)\) is a function of any field of interest. It is known that the conformal invariance must be broken to generate non-trivial magnetic fields [79–90]. Indeed, the coupling between scalar and vector fields, \(\exp [2\phi] F_{\mu\nu} F^{\mu\nu}\), has been proposed in Ref. [81] as a natural origin of large-scale galactic electromagnetic field in the present universe.

Hence a close relation exists between the stable spatial anisotropy of inflationary universe and the broken conformal invariance. Indeed, the mechanism of the broken conformal invariance should induce both non-trivial magnetic fields and a stable spatial anisotropy of spacetime during an inflationary phase. One might also consider some subclasses of the conformal-violating Maxwell theory to see whether the cosmic no-hair conjecture breaks down. In particular, a model with a Ricci scalar non-minimally coupled to the electromagnetic field via a coupling \(Y(R) F_{\mu\nu} F^{\mu\nu}\) [91] has already been considered.

In this paper, we will focus on a possible coupling term with \(I = J^2(X)\) as an algebraic function of the scalar field kinetic term \(X \equiv -\partial^\mu \phi \partial_\mu \phi /2\). Note that \(J\) is considered as an arbitrary function of \(X\). As a result, we will show that a set of Bianchi type I expanding power-law solutions exists. It will also be shown that these solutions are unstable during the inflationary phase in consistent with the cosmic no-hair conjecture in this model. On the other hand, we can also show that stable solutions do exist during the slowly-expanding phase.

This paper will be organized as follows: (i) A brief review and the motivation of this research have been given in Sect. 1. (ii) A complete setup of the proposed model will be presented in Sect. 2. (iii) A set of Bianchi type I power-law inflationary solutions and its stability will be solved and discussed in Sect. 3 and Sect. 4, respectively. (iv) Finally, concluding remarks will be given in Sect. 5.

### 2 Conformal-violating Maxwell model

A conformal-violating Maxwell theory can be described by the general action given by [82–84]

\[
S = \int d^4 x \sqrt{-g} \left[ \frac{R}{2} + X - V(\phi) \right. \\
\left. - \frac{1}{4} I(\phi, R, X, \ldots) F_{\mu\nu} F^{\mu\nu} \right],
\]

(2.1)

with \(F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu\) the field strength of the vector field \(A_\mu\) and \(I(\phi, R, X, \ldots)\) a function of any field of interest. For example, the models with \(I = I(\phi)\) [43–78, 81], \(I = I(R, R_{\mu\nu}, R_{\mu\nu\lambda\kappa})\) [79, 80, 91–96], \(I = I(A^2)\) [97], \(I = I(G)\) [98, 99], and \(I = I \{kF_{\alpha\beta\mu\nu}\} [100, 101]\) have been considered extensively in the literature. Note that the Planck mass \(M_p\) has been set as one for convenience. In this paper, we will study a conformal violating model with \(I = J^2(X)\):

\[
S = \int d^4 x \sqrt{-g} \left[ \frac{R}{2} + X - V(\phi) - \frac{1}{4} J^2(X) F_{\mu\nu} F^{\mu\nu} \right].
\]

(2.2)

As a result, the field equations can be shown to be

\[
\partial_\mu \left( \sqrt{-g} J^2 F^{\mu\nu} \right) = 0,
\]

(2.3)

\[
\left( 1 - \frac{1}{2} J J' F^2 \right) - \frac{1}{2} J J'' + J^2 \right. \partial_{\mu} X \partial^\mu \phi F^2 \\
- \frac{1}{2} J J' \partial^\mu \phi \partial_\mu F^2 - \partial_\phi V = 0,
\]

(2.4)

\[
G_{\mu\nu} - \left( 1 - \frac{1}{2} J J' F^2 \right) \partial_\mu \phi \partial_\nu \phi \\
+ g_{\mu\nu} \left( \frac{1}{2} \partial_{\sigma} \phi \partial^{\sigma} \phi + V + \frac{1}{4} J^2 F^2 \right) - J^2 F_{\mu\nu} F_{\nu\mu} = 0.
\]

(2.5)

Here \(J' \equiv \partial_X J\) denotes the differentiation with respect to the argument of \(J(X)\). In addition, the Einstein tensor is defined as \(G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu}\). Similar to Refs. [43, 44, 47–52], we will focus on the Bianchi type I metric given by

\[
d s^2 = -dt^2 + \exp [2\alpha(t) - 4\sigma(t)] dx^2 \\
+ \exp [2\alpha(t) + 2\sigma(t)] \left( dy^2 + dz^2 \right).
\]

(2.6)

In addition, the scalar field \(\phi\) and the vector field \(A_\mu\) will be chosen as \(\phi = \phi(t)\) and \(A_\mu = (0, A_x(t), 0, 0)\) respectively. As a result, Eq. (2.3) can be integrated directly as

\[
\dot{A}_x(t) = J^{-2}(X) \exp [-\alpha - 4\sigma] \rho_A,
\]

(2.7)

with \(\rho_A\) the constant of integration [43, 44]. Hence we can rewrite Eq. (2.4) as

\[
\{ 1 + J^{-3} \left[ J' + \phi^2 \left( J'' - 3J^{-1} J'^2 \right) \right] \exp [-4\alpha - 4\sigma] \rho_A^2 \} \dot{\phi} \\
= -3\dot{\alpha} \phi + (\dot{\alpha} + 4\dot{\sigma}) \phi J^{-3} J' \exp [-4\alpha - 4\sigma] \rho_A^2 - \partial_\phi V.
\]

(2.8)
In addition, the non-vanishing components of the Einstein equation (2.5) can be shown to be:

\[ \begin{align*}
\ddot{a}^2 &= \dot{a}^2 + \frac{1}{3} \left[ \ddot{\phi}^2 + V + \frac{J^2}{2} \left( 2\dot{\phi}^2 J^{-1} J' + 1 \right) \right] \times \exp \left[ -4\alpha - 4\sigma \right] \rho_A^2, \\
\ddot{a} &= -3\dot{a}^2 + V + \frac{J^2}{6} \left( 3\dot{\phi}^2 J^{-1} J' + 1 \right) \times \exp \left[ -4\alpha - 4\sigma \right] \rho_A^2, \\
\dot{a} &= -3\dot{a} \sigma + \frac{J^2}{3} \exp \left[ -4\alpha - 4\sigma \right] \rho_A^2.
\end{align*} \] (2.9)

(2.10)

(2.11)

Note that the Friedmann equation (2.9) is the $G_0^0$ component equation, Eq. (2.10) is the $(3G_0^0 + G_1^1 + 2G_2^2)$ equation, and Eq. (2.11) is the $(G_1^1 - G_2^2)$ equation.

3 Anisotropic power-law solutions

We will try to find a set of power-law solutions for the proposed model (2.1) in this section. In particular, we would like to obtain a new set of power-law analytic solutions with the form [43,44,47–52]:

\[ \alpha = \xi \log (t); \quad \sigma = \eta \log (t); \quad \phi = \xi \log (t) + \phi_0. \] (3.1)

Note that this set of power-law ansatz is the key to obtain a consistent set of power-law solutions. For simplicity, we will focus on the exponential scalar potential given by:

\[ V (\phi) = V_0 \exp \left[ \lambda \phi \right], \] (3.2)

along with the power-law kinetic function:

\[ J (X) = J_0 X^n. \] (3.3)

Here $V_0$, $J_0$, $\phi_0$, and $\lambda$ are constants specifying the boundary information of these potential and kinetic functions. In addition, the constants $\lambda$ and $n$ are assumed to be positive. For convenience, we will also introduce the following new variables:

\[ u = V_0 \exp [\lambda \phi_0], \] (3.4)

\[ v = \rho_A^2 J_0^{-2} \left( \frac{\xi^2}{2} \right)^{-2n}. \] (3.5)

As a result, we can derive the following set of algebraic equations from the field equations:

\[ \begin{align*}
&\left[ \frac{2n}{\xi^2} (4n + 1) v - 1 \right] \xi + 3\xi \xi \\
&- \frac{2n}{\xi} (\zeta + 4\eta) v + \lambda u = 0,
\end{align*} \] (3.6)

\[ \zeta^2 - \eta^2 - \frac{\xi^2}{6} - \frac{u}{3} - \frac{1}{6} (4n + 1) v = 0, \] (3.7)

\[ -\zeta + 3\xi^2 - u - \frac{1}{6} (6n + 1) v = 0, \] (3.8)

\[ (3\zeta - 1) \eta - \frac{v}{3} = 0, \] (3.9)

along with the following constraints:

\[ \lambda \xi = -2, \] (3.10)

\[ \zeta + \eta - n - \frac{1}{2} = 0. \] (3.11)

The constraint (3.11) indicates that $n$ behaves similar to the ratio $\rho/\lambda$ discussed in the KSW model in Refs. [43,44] with $I = f^2 (\phi) \sim \exp [2\rho \phi]$ and $V (\phi) \sim \exp [\lambda \phi]$. This is, however, the only similarity between the KSW model [43, 44] and our proposed model. Indeed, it turns out that all field equations in this paper are not alike as compared to the field equations of the KSW model. With the constraint (3.10), the variable $v$ can be written as

\[ v = \rho_A^2 J_0^{-2} \left( \frac{\xi^2}{2} \right)^{2n}. \] (3.12)

Note that both variables, $u$ and $v$, are assumed to be positive. Given $n$ shown in Eq. (3.11), Eqs. (3.8) and (3.9) can be solved to give:

\[ u = \frac{1}{4} (3\zeta - 1) \left[ (6n + 1) (2\zeta - 2n - 1) + 4\zeta \right], \] (3.13)

\[ v = -\frac{3}{2} (3\zeta - 1) (2\zeta - 2n - 1). \] (3.14)

With $\eta$, $u$, and $v$ defined above, scalar field equation (3.6) and Friedmann equation (3.7) can be reduced as

\[ (3\zeta - 1) \left[ 36n \xi^2 - 6 \left( 6n^2 + 3n - 1 \right) \zeta \right. \]
\[ \left. - 2n - 8\xi^2 - 1 \right] = 0, \] (3.15)

\[ 36n \xi^2 - 6 \left( 6n^2 + 3n - 1 \right) \zeta - 2n - 8\xi^2 - 1 = 0, \] (3.16)

respectively. It turns out that both Eqs. (3.15) and (3.16) lead to the non-trivial solutions

\[ \xi_{\pm} = \frac{6n^2 + 3n - 1}{12n} \pm \frac{\sqrt{\Delta}}{12\lambda n}. \] (3.17)

\[ \Delta = \lambda^2 \left( 36n^4 + 36n^3 + 5n^2 - 2n + 1 \right) + 32n \] (3.18)
for $\zeta \neq 1/3$. Since $n$ is assumed to be positive and $\zeta > \eta$, $\zeta_+$ can be shown to be only the consistent solution:

$$\zeta = \zeta_+ = \frac{6n^2 + 3n - 1}{12n} + \frac{\sqrt{\lambda^2 (36n^4 + 36n^3 + 5n^2 - 2n + 1) + 32n}}{12\lambda n}, \quad (3.19)$$

In addition, the variable $\eta$ becomes

$$\eta = \frac{6n^2 + 3n + 1}{12n} - \frac{\sqrt{\lambda^2 (36n^4 + 36n^3 + 5n^2 - 2n + 1) + 32n}}{12\lambda n}. \quad (3.20)$$

It is clear that $\eta < \zeta = \zeta_+$ as expected. Following Refs. [43, 44], the anisotropy parameter is given by

$$\Sigma = \frac{\dot{\sigma}}{H} = \frac{(6n^2 + 3n + 1)\lambda - \sqrt{\lambda^2 (36n^4 + 36n^3 + 5n^2 - 2n + 1) + 32n}}{(6n^2 + 3n - 1)\lambda + \sqrt{\lambda^2 (36n^4 + 36n^3 + 5n^2 - 2n + 1) + 32n}}, \quad (3.21)$$

The positivity of $\nu$ implies that $\eta > 0$ with the help of Eq. (3.11) provided that $\zeta > 1/3$. Hence, the positivity of $\eta$ leads to a constraint of $n$ given by

$$n > \frac{4 - \lambda^2}{2\lambda^2} = \frac{2}{\lambda^2} - 1/2, \quad (3.22)$$

with the help of Eq. (3.20). Note also that for an anisotropically expanding solution, the following constraints $\zeta + \eta > 0$ and $\zeta - 2\eta > 0$ need to be satisfied. It is apparent that the constraint $\zeta + \eta > 0$ holds for positive $n$. In addition, the constraint $\zeta - 2\eta > 0$ leads to the inequality:

$$\lambda^2 \left(8n^3 + 8n^2 - 1\right) + 8 > 0. \quad (3.23)$$

The inequality (3.23) holds apparently for all $n > (\sqrt{5} - 1)/4 \approx 0.309$ if $\lambda \geq 0$. Hence, expanding solutions exist for the canonical model with $n = 1$. For $0 < n < (\sqrt{5} - 1)/4$, the above inequality will depend, however, on the value of $\lambda$. Note also that the parameter $\Delta$ is positive definite if the inequality (3.23) holds. Finally, with the help of Eq. (3.13), the positivity of $u$ leads to the inequality

$$(6n + 1) (2\zeta - 2n - 1) + 4\zeta > 0. \quad (3.24)$$

or equivalently,

$$0 < n < \zeta - \frac{1}{6}. \quad (3.25)$$

Consequently, the following constraint on $\eta$ can be obtained from Eq. (3.11) as

$$\eta < \frac{1}{3}, \quad (3.26)$$

It appears that there are constraints of $n$ given by the Eqs. (3.22), (3.23), and (3.25) for the expanding solution with $\zeta + \eta > 0$ and $\zeta - 2\eta > 0$. Note that we are interested in the inflationary phase solutions with the following constraints $\zeta + \eta \gg 1$ and $\zeta - 2\eta \gg 1$. As a result, the constraint $\zeta + \eta \gg 1$ and the Eq. (3.11) imply that

$$\zeta + \eta = n + \frac{1}{2} \gg 1, \quad (3.27)$$

or equivalently,

$$n \gg 1. \quad (3.28)$$

Consequently, the field variables can be approximated as

$$\zeta \simeq n \gg 1; \quad u \simeq \frac{3}{4} n^2 \gg 1; \quad v \simeq \frac{9}{4} \gg 1. \quad (3.29)$$

during the inflationary phase with $n \gg 1$. It is also straightforward to show that $\eta < 1/3$ and $\Sigma/H < 1$ during the inflationary phase. For example, $\zeta \simeq 40.4974$, $\eta \simeq 0.00264$, and $\Sigma/H \simeq 0.000065$ if we choose $n = 40$ and $\lambda = 1$. For a comparison with the KSW model [43,44], we will have $\zeta_{\text{KSW}} = 40.1831$, $\eta_{\text{KSW}} = 0.316872$, and $\Sigma/H_{\text{KSW}} = 0.007886$ if we choose $\rho = 40$ and $\lambda = 1$ such that $n = \rho/\lambda$. It is clear that the spatial anisotropy parameter in the $J^2(X)F^2$ model is much smaller than that of the KSW model with $f(\phi)F^2$. On the other hand the isotropy parameters are quite similar to each other.

### 4 Stability analysis of anisotropic solutions

In this section, we will try to show that the new set of power-law solutions are unstable during the inflationary phase. On the other hand, this new set of power-law solutions is stable during the slowly-expanding phase for a limited $\lambda$-$n$ domain.

#### 4.1 Inflationary phase

In order to understand the stability of the set of power-law solutions, we will consider the power-law perturbation of the field equations with $\delta a = A_\alpha t^\alpha$, $\delta \sigma = A_\sigma t^\sigma$, and $\delta \phi = A_\phi t^\phi$ [47–52]. Perturbing Eqs. (2.8), (2.10), and (2.11) leads to a set of algebraic equations that can be cast as a matrix equation:
As a result, this determinant equation leads to a polynomial equation of \( m \):

\[
mf(m) = \left(a_0m^5 + a_5m^4 + a_4m^3 + a_3m^2 + a_2m + a_1\right) = 0, \tag{4.6}
\]

with the coefficients \( a_i \)'s \( (i = 1 - 6) \) given by

\[
a_0 = -\frac{1}{2} (4\lambda^2 v^2 + \lambda^2 v - 2), \tag{4.7}
\]

\[
a_5 = -\lambda^2 v \left[ 8n^2 + 8(2\zeta - \eta)n + \frac{1}{2} (8\zeta - 4\eta - 1) \right] + 3 (4\zeta - 1), \tag{4.8}
\]

\[
a_4 = -2\lambda^2 v (36\zeta + 3v - 8)n^3 - \lambda^2 v \left[ 18\zeta^2 - 72\zeta\eta + 22\zeta + 16\eta + 3v - 6 + \frac{12}{\lambda^2} \right] n^2 - \frac{\lambda^2 v}{2} \left[ 9\zeta^2 - 36\zeta\eta + 2\zeta + 8\eta + 2v - 1 - \frac{4}{\lambda^2} \right] n + 45\zeta^2 - 24\zeta + \lambda^2 u + 2v + 3, \tag{4.9}
\]

\[
a_3 = -2\lambda^2 v \left[ 72\zeta^2 + v (9\zeta + 1) - 36\zeta + 4 \right] n^3 + \lambda^2 v \left[ 18\zeta^2 (2\zeta - 5) + 8\eta (18\zeta^2 - 9\zeta + 1) \right.
\]

\[
\left. - v (7\zeta - 14\eta + 3) + 38\zeta - 4 - \frac{12}{\lambda^2} (3\zeta - 1) \right] n^2 + \frac{\lambda^2 v}{2} \left[ 9\zeta^2 (2\zeta - 3) + 2\eta (36\zeta^2 - 18\zeta + 2) \right.
\]

\[
\left. - 2v (4\zeta - 5\eta) + 10\zeta + 2u - 1 + \frac{12}{\lambda^2} (3\zeta - 2\eta - 1) \right] n + 3\zeta (18\zeta^2 - 15\zeta + 4) + 2v (8\zeta - 2 - 6\zeta^2 - 17). \tag{4.10}
\]

Positive root to Eq. (4.6) does not exist if all the coefficients \( a_i \) are positive (or negative). As a result, the corresponding anisotropic solution is stable. On the other hand, Eq. (4.6) admits at least one positive root if \( a_1a_6 < 0 \). Therefore the corresponding anisotropic solution is unstable if \( a_1a_6 < 0 \).

We can show that \( a_6 < 0 \) with the help of the inequality (3.22). In addition, the leading term of \( a_1 \) is given by

\[
a_1 \simeq 2\lambda^2 uv \left[ 18n^3 + 3 \frac{3}{2} n^2 + n - \frac{4}{\lambda^2} \right], \tag{4.13}
\]

for \( n \gg 1 \). Hence the inequality (3.22) implies that \( a_1 > 0 \) for \( n \gg 1 \). This implies that the anisotropic power-law solution of the \( J^2(X)F^2 \) model is indeed unstable during the inflationary phase in contrast to the results of the KSW model. The result is, however, consistent with the cosmic no-hair conjecture. It shows that the non-trivial coupling, \( I (\phi, X, ...) F_{\mu\nu} F^{\mu\nu} \) is capable of inducing a small spatial-anisotropy for the evolution of our current universe.

Note that the stability of the anisotropy depends on the choice of the function \( I \) coupled to the \( U_1 \) gauge field. In particular, the anisotropy will survive the inflation if \( I \) is chosen to be a canonical function of a scalar field as shown in the KSW model \([43, 44, 49–52]\). On the other hand, if \( I \) is chosen as a function of the kinetic term of the scalar field, the anisotropy is unstable during the inflationary phase. As a result, the power-law solutions shows that our universe acts in favor of the forming of an isotropic (de Sitter) space consistent with that the cosmic no-hair conjecture predicts.
4.2 Slowly expanding phase

Even the power-law solution is unstable during the inflationary phase, it will be interesting to know whether it is unstable during the slowly-expanding phase. Indeed, we will show that the new set of power-law solutions is stable during the slowly-expanding phase for a small $\lambda$-domain. Note that $\zeta + \eta$ and $\zeta - 2\eta$ are of order one, $O(1)$, for the slowly expanding phase. Note again that unstable anisotropic inflationary solutions for the large $n$ as proved earlier in this section.

In addition, we would like to see whether the new set of slowly expanding solutions is indeed a set of attractive solutions for the parameters $\lambda$ and $n$ chosen within the red region in Fig. 1. Following Refs. [43,44,49–52], we will introduce the dynamical variables

$$\dot{X} = \frac{\dot{X}}{\dot{\alpha}}; \quad \dot{Y} = \frac{\dot{Y}}{\dot{\alpha}}; \quad \dot{Z} = \frac{\dot{Z}}{\dot{\alpha}} \left( \frac{\dot{\alpha}^2}{\alpha^2} \right)^{-n} \exp[-2\alpha - 2\sigma].$$

(4.14)

As a result, a set of autonomous equations of the dynamical system can be derived from the field Eqs. (2.8), (2.10), and (2.11) as

$$\begin{align*}
\frac{d\dot{X}}{d\alpha} &= -\frac{\dot{\alpha}}{\alpha^2} \dot{X} + \frac{\dot{\sigma}}{\alpha^2} \\
&= \dot{X} \left[ 3 \left( \dot{X}^2 - 1 \right) + \frac{Y^2}{2} + \left( n + \frac{1}{3} \right) Z^2 \right] + \frac{Z^2}{3},
\end{align*}$$

(4.15)

$$\begin{align*}
\frac{d\dot{Y}}{d\alpha} &= \frac{\dot{\alpha}}{\alpha^2} Y + \frac{\dot{\phi}}{\alpha^2} \\
&= Y \left[ 3\dot{X}^2 + \frac{Y^2}{2} + \left( n + \frac{1}{3} \right) Z^2 \right]
+ \frac{1}{Y^2 - 2n(4\lambda + 1)Z^2} \left\{ \lambda Y \left[ 3 \left( \dot{X}^2 - 1 \right) \right] + \frac{Y^2}{2} \right.
+ \left( 2n + \frac{1}{2} \right) Z^2 \right] + 2n \left( 4\dot{X} + 1 \right) Z^2 - 3Y^2 \right\},
\end{align*}$$

(4.16)

$$\begin{align*}
\frac{d\dot{Z}}{d\alpha} &= -Z \left[ \frac{\dot{\alpha}}{\alpha^2} + 2\dot{X} + 2\frac{2n \dot{\phi}}{Y \alpha^2} \right] \\
&= Z \left[ 3\dot{X}^2 + \frac{Y^2}{2} + \left( n + \frac{1}{3} \right) Z^2 - 2\dot{X} - 2 \right]
- \frac{2n}{Y^2 - 2n(4\lambda + 1)Z^2} \left\{ \lambda Y \left[ 3 \left( \dot{X}^2 - 1 \right) \right] \right.
+ \left( 2n + \frac{1}{2} \right) Z^2 \right] + 2n \left( 4\dot{X} + 1 \right) Z^2 \right.
\left. - 3Y^2 \right\}.
\end{align*}$$

(4.17)

Note that we have used the Hamiltonian equation (2.9)

$$\frac{V}{\dot{\alpha}^2} = -3 \left( \dot{X}^2 - 1 \right) - \frac{Y^2}{2} - \left( 2n + \frac{1}{2} \right) Z^2,$$

(4.18)

in order to derive the above equations. Note that the anisotropic fixed points are solutions of the autonomous equations $d\dot{X}/d\alpha = dY/d\alpha = dZ/d\alpha = 0$. As a result, we can obtain, from equations $dY/d\alpha = dZ/d\alpha = 0$, a relation given by

$$3\dot{X}^2 + \frac{Y^2}{2} + \left( n + \frac{1}{3} \right) Z^2 = \frac{2(\dot{X} + 1)}{2n + 1}.$$  

(4.19)

The equation $d\dot{X}/d\alpha = 0$ can thus be reduced to

$$Z^2 = -3\dot{X} \left[ \frac{2(\dot{X} + 1)}{2n + 1} - 3 \right].$$

(4.20)

On the other hand, the equations $d\dot{X}/d\alpha = dY/d\alpha = dZ/d\alpha = 0$ will lead the Hamiltonian constraint (4.18) given by

$$\frac{d}{d\alpha} \left( \frac{V}{\dot{\alpha}^2} \right) = 0.$$

(4.21)
Hence we have
\[
\frac{\ddot{\alpha}}{\alpha^2} = \frac{\lambda}{2} Y, \tag{4.22}
\]
or equivalently,
\[
3\dot{X}^2 + \frac{Y^2}{2} + \left(n + \frac{1}{3}\right)Z^2 = -\frac{\lambda}{2} Y. \tag{4.23}
\]

As a result, the relation between \(\dot{X}\) and \(Y\) can be shown to be
\[
Y = -\frac{4(\dot{X} + 1)}{\lambda(2n + 1)} \tag{4.24}
\]
from Eqs. (4.19) and (4.23). With the useful relations shown in Eqs. (4.20) and (4.24), we are able to rewrite Eq. (4.19) as an equation of \(\dot{X}\) given by
\[
[\lambda^2(2n + 1) + 8]\dot{X}^2 + [\lambda^2(36n^3 + 36n^2 + 7n - 1) + 16]\dot{X} - 2\lambda^2(2n + 1) + 8 = 0. \tag{4.25}
\]
Consequently, non-trivial solutions of \(\dot{X}\) can be solved as
\[
\dot{X}_\pm = -\frac{\lambda^2(2n + 1)(18n^2 + 9n - 1) + 16 \pm 3\lambda(2n + 1)\sqrt{\lambda^2(36n^4 + 36n^3 + 5n^2 - 2n + 1) + 32n}}{2[\lambda^2(2n + 1) + 8]}. \tag{4.26}
\]

It is apparent that the \(\dot{X}_-\) is identical to the ratio \(\Sigma/H\) of the anisotropic power-law solution found in the previous section. In other words, \(\dot{X}_-\) is exactly the anisotropic fixed point equivalent to the anisotropic power-law solution we found earlier.

Hinted by the allowed region of \(\lambda\) and \(n\) for the existence of stable expanding-solutions shown above, we can, for example, examine the attractor behavior of the anisotropic fixed point for \(n = 1\) (corresponding to the canonical kinetic term) and \(\lambda = 1.25\). Note that for this choice the scale factors will be \(\zeta \simeq 1.5\) and \(\eta \simeq 0.015 \ll \zeta\). The result is shown in Fig. 2.

As a result, the anisotropic fixed point can be shown to be the attractor to the dynamical system as expected. This result shows that the \(J^2(X)F^2\) model does admit stable and attractive anisotropic expanding solutions even this model does not admit any stable and attractive anisotropic inflationary solution. Nevertheless, the cosmic no-hair conjecture is indeed violated in the \(J^2(X)F^2\) model. A small anisotropy will still sustain during the slowly-expanding phase and leads to a small anisotropy observed today.

5 Conclusions

Inflation has been considered as a main paradigm in the current cosmology. It is successful in solving some fundamental questions in cosmology. The predictions are also consistent with the observations of the cosmic microwave background radiation. In addition, the cosmic no-hair conjecture explains the physical origin of the highly isotropic universe. This conjecture is based on a belief that the vacuum energy
dome" would erase any classical hair. The conformal-violating Maxwell model \[79–90\] proposed in Refs. \[43,44\] provides a counter-example to the cosmic no-hair theorem. Hence we propose to study a conformal-violating Maxwell model with a coupling term, \( J^2(X) F^2 = J^2 X^{2n} F^2 \).

In contrast to results found in \[43,44,49–52\], we found that the new model does not admit any stable and attractive Bianchi type I inflationary solution. By a careful stability analysis, we have found, however, that the proposed model does admit stable and attractive Bianchi type I expanding solutions in the slowly-expanding phase. Hence this model provides another counter-example to the cosmic no-hair conjecture with a tiny spatial hair. The results shown in this paper suggest that a correlation between an anisotropy of universe space and a broken conformal invariance deserve more attention.

Moreover, small anisotropy is required to explain the origin of large-scale galactic electromagnetic field in the present universe. It would be interesting to examine the validity of the cosmic no-hair conjecture for some other possible coupling terms in the conformal-violating theory. For example, those models that have been discussed recently, e.g., those models that have been discussed recently, those models that have been discussed recently, provide a counter-example to the cosmic no-hair theorem. For example, those models that have been discussed recently, we suggest that a correlation between an anisotropy of universe space and a broken conformal invariance deserve more attention.

Note added: The appearance of Ref. \[108\] came to our attention when are finalizing our paper. Motivated by Refs. \[63,109–111\], Ref. \[108\] proposes an extension of the KSW model with \( f(\phi) \rightarrow f(\phi, X) \) similar to ours. In particular, Ref. \[108\] points out that no small-anisotropy inflationary solutions exists for \( f(X) \propto X^{-n} \) in contrast to our model with \( f(X) \propto X^n \).

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References

1. A.H. Guth. The inflationary universe: A possible solution to the horizon and flatness problems. Phys. Rev. D 23, 347 (1981)
2. A.D. Linde. A new inflationary universe scenario: A possible solution of the horizon, flatness, homogeneity, isotropy and primordial monopole problems. Phys. Lett. 108, B389 (1982)
3. A.D. Linde. Chaotic inflation. Phys. Lett. 129, B177 (1983)
4. E. Komatsu, et al., [WMAP Collaboration]. Seven-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: Cosmological interpretation, Astrophys. J. Suppl. 192, 18 (2011). arXiv:1001.4538
5. G. Hinshaw, et al., [WMAP Collaboration]. Nine-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: Cosmological parameter results, Astrophys. J. Suppl. 208, 19 (2013). arXiv:1212.5226
6. P.A.R. Ade, et al., [Planck Collaboration]. Planck 2015 results. XX. Constraints on inflation. Astron. Astrophys. 594, A20 (2016). arXiv:1502.02114
7. P.A.R. Ade, et al., [Planck Collaboration]. Planck 2015 results. XVI. Isotropy and statistics of the CMB. Astron. Astrophys. 594, A16 (2016). arXiv:1506.07135
8. T. Buchert, A.A. Coles, H. Kleinert, B.F. Roukema, D.L. Wiltshire, Observational challenges for the standard FLRW model. Int. J. Mod. Phys. D 25, 1630007 (2016). arXiv:1512.03313
9. G.F.R. Ellis, M.A.H. MacCallum, A class of homogeneous cosmological models. Commun. Math. Phys. 12, 108 (1969)
10. G.F.R. Ellis, The Bianchi models: Then and now. Gen. Rel. Grav. 38, 1003 (2006)
11. C. Pitrou, T.S. Pereira, J.P. Uzan, Predictions from an anisotropic inflationary era. J. Cosmol. Astropart. Phys. 04, 004 (2008). arXiv:0801.3596
12. A.E. Gumrukcuoglu, C.R. Contaldi, M. Peloso, Inflationary perturbations in anisotropic backgrounds and their imprint on the CMB. J. Cosmol. Astropart. Phys. 07, 005 (2007). arXiv:0707.4179
13. G.W. Gibbons, S.W. Hawking, Cosmological event horizons, thermodynamics, and particle creation. Phys. Rev. D 15, 2738 (1977)
14. S.W. Hawking, I.G. Moss, Supercooled phase transitions in the very early universe. Phys. Lett. 110B, 35 (1982)
15. R.M. Wald, Asymptotic behavior of homogeneous cosmological models in the presence of a positive cosmological constant. Phys. Rev. D 28, 2118 (1983)
16. M. Kleban, L. Senatore, Inhomogeneous anisotropic cosmology. J. Cosmol. Astropart. Phys. 10, 022 (2016). arXiv:1602.03520
17. W.E. East, M. Kleban, A. Linde, L. Senatore, Beginning inflation in an inhomogeneous universe. J. Cosmol. Astropart. Phys. 09, 010 (2016). arXiv:1511.05143
18. J.D. Barrow, Cosmic no hair theorems and inflation. Phys. Lett. B 187, 12 (1987)
19. Y. Kitada, K. Maeda, Cosmic no hair theorem in power law inflation. Phys. Rev. D 45, 1416 (1992)
20. S.M. Carroll, A. Chatwin-Davies, Cosmic equilibration: A holographic no-hair theorem from the generalized second law. arXiv:1703.09241
21. D. Saadeh, S.M. Feeney, A. Pontzen, H.V. Peiris, J.D. McEwen, How isotropic is the universe? Phys. Rev. Lett. 117, 131302 (2016). arXiv:1605.07178
22. J.D. Barrow, S. Hervik, Anisotropically inflating universes. Phys. Rev. D 73, 023007 (2006). arXiv:gr-qc/0511127
23. J.D. Barrow, S. Hervik, On the evolution of universes in quadratic theories of gravity. Phys. Rev. D 74, 124017 (2006). arXiv:gr-qc/0610013
24. J.D. Barrow, S. Hervik, Simple types of anisotropic inflation. Phys. Rev. D 81, 023513 (2010). arXiv:0911.3805
25. J. Middleton, On the existence of anisotropic cosmological models in higher order theories of gravity. Class. Quant. Grav. 27, 225013 (2010). arXiv:1007.4669
123

90. J.D. Barrow, C.G. Tsagas, K. Yamamoto, Origin of cosmological magnetic field survival. J. Cosmol. Astropart. Phys. 02, 030 (2007). arXiv:astro-ph/06111701

91. M. Adak, O. Akarsu, T. Dereli, O. Sert, Anisotropic inflation with a non-minimally coupled electromagnetic field to gravity. J. Cosmol. Astropart. Phys. 11, 026 (2017). arXiv:1611.03393

92. F.D. Mazzitelli, F.M. Spedalieri, Scalar electrodynamics and primordial magnetic fields. Phys. Rev. D 52, 6694 (1995). arXiv:astro-ph/9505140

93. L. Campanelli, P. Cea, G.L. Fogli, L. Tedesco, Inflation-produced magnetic fields in $R^n F^2$ and $JF^2$ models. Phys. Rev. D 77, 123002 (2008). arXiv:0802.2630

94. K. Bamba, S.D. Odintsov, Inflation and late-time cosmic acceleration in non-minimal Maxwell-F($R$) gravity and the generation of large-scale magnetic fields. J. Cosmol. Astropart. Phys. 04, 024 (2008). arXiv:0801.0954

95. K.E. Kunze, Large scale magnetic fields from gravitationally coupled electrodynamics. Phys. Rev. D 81, 043526 (2010). arXiv:0911.1101

96. K.E. Kunze, Completing magnetic field generation from gravitationally coupled electrodynamics with the curvaton mechanism. Phys. Rev. D 87, 063505 (2013). arXiv:1210.6899

97. A. Golovnev, On cosmic inflation in vector field theories. Class. Quant. Grav. 28, 245018 (2011). arXiv:1109.4838

98. J. Sadeghi, M.R. Setare, A. Banijamali, Non-minimal Maxwell-modified Gauss–Bonnet cosmologies: inflation and dark energy. Eur. Phys. J. C 64, 433 (2009). arXiv:0906.0713

99. G. Esposito-Farese, C. Pitrou, J.P. Uzan, Vector theories in cosmology. Phys. Rev. D 81, 063519 (2010). arXiv:0912.0481

100. L. Campanelli, A model of universe anisotropization. Phys. Rev. D 80, 063006 (2009). arXiv:0907.3703

101. V.A. Kostelecky, Gravity, Lorentz violation, and the standard model. Phys. Rev. D 69, 105009 (2004). arXiv:hep-th/0312310

102. M. Gasperini, M. Giovannini, G. Veneziano, Primordial magnetic fields from string cosmology. Phys. Rev. Lett. 75, 3796 (1995). arXiv:hep-th/9504083

103. D. Lemoine, M. Lemoine, Primordial magnetic fields in string cosmology. Phys. Rev. D 52, 1955 (1995)

104. K. Bamba, J. Yokoyama, Large scale magnetic fields from inflation due to a $CPT$-even Chern-Simons-like term with Kalb-Ramond and scalar fields. Eur. Phys. J. C 72, 1978 (2012). arXiv:1108.0151

105. J. Martin, J. Yokoyama, Generation of large-scale magnetic fields in single-field inflation. J. Cosmol. Astropart. Phys. 01, 025 (2008). arXiv:0711.4307

106. K. Bamba, C.Q. Geng, S.H. Ho, W.F. Kao, Large-scale magnetic fields from inflation due to a $CPT$-even Chern-Simons-like term with Kalb-Ramond and scalar fields. Eur. Phys. J. C 72, 1978 (2012). arXiv:1108.0151

107. K. Dimopoulos, D. Wills, I. Zavala, Statistical anisotropy from inflation in noncommutative spacetime. Phys. Rev. D 70, 083508 (2004). arXiv:hep-ph/0409237

108. J. Martin, J. Yokoyama, Generation of large-scale magnetic fields in single-field inflation. J. Cosmol. Astropart. Phys. 01, 025 (2008). arXiv:0711.4307

109. K. Bamba, J. Yokoyama, Large-scale magnetic fields from dilaton inflation in noncommutative spacetime. Phys. Rev. D 70, 083508 (2004). arXiv:hep-ph/0409237

110. Y.A. Kostelecky, Gravity, Lorentz violation, and the standard model. Phys. Rev. D 69, 105009 (2004). arXiv:hep-th/0312310

111. X. Chen, Y. Wang, Z.Z. Xianyu, Standard model background of vector curvaton in D-brane inflation. Nucl. Phys. B 868, 120 (2013). arXiv:1108.4424

112. T. Rostami, A. Karami, H. Firouzjahi, Effective field theory of statistical anisotropies for primordial bispectrum and gravitational waves. J. Cosmol. Astropart. Phys. 06, 039 (2017). arXiv:1702.03744

113. X. Chen, Y. Wang, Z.Z. Xianyu, Standard model background of the cosmological collider. Phys. Rev. Lett. 118, 261302 (2017). arXiv:1610.06597