The important role of scalar field in cosmology was noticed by a number of authors. Due to the fact that the scalar field possesses zero spin, it was basically considered in isotropic cosmological models. If considered in an anisotropic model, the linear scalar field does not lead to isotropization of expansion process. One needs to introduce scalar field with non-linear potential for the isotropization process to take place. In this paper the general form of scalar field potentials leading to the asymptotic isotropization in case of Bianchi type-I cosmological model, and inflationary regime in case of isotropic space-time is obtained. In doing so we solved both direct and inverse problem, where by direct problem we mean to find metric functions and scalar field for the given potential, whereas, the inverse problem means to find the potential and scalar field for the given metric function. The scalar field potentials leading to the inflation and isotropization were found both for harmonic and proper synchronic time.

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I. INTRODUCTION

The discovery of the accelerating mode of expansion of the Universe has produced a large number of papers on its possible explanation [1–3]. As a source of late time acceleration beside the traditional cosmological constant [4–7], a number of other possibilities were also suggested. To name a few are quintessence [8–11], Chaplygin gas [12–15], phantom type dark energy [16, 17], oscillating dark energy [18–20], models with interaction between dark energy and dark matter [21, 22], models with tachyon matter [23–27], quintom matter [28, 29], models with spinor field [30–36].

Despite the varieties of sources able to explain the late time acceleration, the scalar field reserves a special place in this hierarchy. And the central idea is to find the suitable potential that
allows accelerated expansion. Due to the fact that the scalar field possesses zero spin, it was basically considered in isotropic cosmological models. In this paper, within the scope of Bianchi type-I cosmological model we study the role of a scalar field with nonlinear potential leading to both isotropization and inflation.

II. BASIC EQUATIONS AND THEIR GENERAL SOLUTIONS

We consider the simplest possible scalar field model within the framework of a BI cosmological gravitational field given by the Lagrangian density

\[ \mathcal{L} = \frac{R}{2\kappa} + \frac{1}{2} \phi_{,\eta} \phi^{,\eta} - V(\phi), \]  

(2.1)

where \( \phi \) stands for real scalar field, \( V(\phi) \) is the potential and \( R \) is the scalar curvature. The natural units \( \hbar = c = 1 \) are used. The cosmological gravitational field is given by the Bianchi type-I (BI) metric in the form

\[ ds^2 = e^{2\alpha} dt^2 - e^{2\beta_1} dx^2 - e^{2\beta_2} dy^2 - e^{2\beta_3} dz^2. \]  

(2.2)

In what follows we suppose that the scalar field \( \phi \) and the metric functions \( \alpha, \beta_1, \beta_2, \beta_3 \) depend on \( t \) only. We also assume that the metric functions satisfy the harmonic coordinate condition

\[ \alpha = \beta_1 + \beta_2 + \beta_3, \]  

(2.3)

implying the simplest form of the equation of motion.

Written in the form

\[ R^\nu_{\mu} = -\kappa \left( T^\nu_{\mu} - \frac{1}{2} \delta^\nu_{\mu} R \right), \]  

(2.4)

the Einstein equations corresponding to the metric (2.2) in account of (2.3) read

\[ e^{-2\alpha} \left( \ddot{\alpha} - \dot{\alpha}^2 + \dot{\beta}_1^2 + \dot{\beta}_2^2 + \dot{\beta}_3^2 \right) = -\kappa \left( T^0_0 - \frac{1}{2} T \right), \]  

(2.5a)

\[ e^{-2\alpha} \dot{\beta}_1 = -\kappa \left( T^1_1 - \frac{1}{2} T \right), \]  

(2.5b)

\[ e^{-2\alpha} \dot{\beta}_2 = -\kappa \left( T^2_2 - \frac{1}{2} T \right), \]  

(2.5c)

\[ e^{-2\alpha} \dot{\beta}_3 = -\kappa \left( T^3_3 - \frac{1}{2} T \right), \]  

(2.5d)

where over dot means differentiation with respect to \( t \) and

\[ T^\nu_{\mu} = \phi_{,\nu} \phi^{,\mu} - \delta^\nu_{\mu} \left( \frac{1}{2} \phi_{,\eta} \phi^{,\eta} - V(\phi) \right), \]  

(2.6)

is the energy-momentum tensor of the scalar field.

The scalar field equation corresponding to the metric (2.1) has the form

\[ \frac{1}{\sqrt{-g}} \frac{\partial}{\partial x^\mu} \left( \sqrt{-g} g^{\mu\nu} \phi_{,\nu} \right) + \frac{dV}{d\phi} = 0. \]  

(2.7)

which on account of (2.3) gives

\[ \dot{\phi} = -\frac{dV}{d\phi} e^{2\alpha}. \]  

(2.8)
For the components of energy-momentum tensor in this case we find
\[
T_{00} = \frac{1}{2} \dot{\phi}^2 e^{-2\alpha} + V(\phi), \quad (2.9a)
\]
\[
T_{11} = T_{22} = T_{33} = -\frac{1}{2} \dot{\phi}^2 e^{-2\alpha} + V(\phi) \quad (2.9b)
\]
In view of (2.9) system of Einstein equations now take the form
\[
\ddot{\alpha} - \dot{\alpha}^2 + \beta_1^2 + \beta_2^2 + \beta_3^2 = -\kappa \left( \phi^2 - V(\phi) e^{2\alpha} \right), \quad (2.10a)
\]
\[
\dot{\beta}_1 = \kappa V(\phi) e^{2\alpha}, \quad (2.10b)
\]
\[
\dot{\beta}_2 = \kappa V(\phi) e^{2\alpha}, \quad (2.10c)
\]
\[
\dot{\beta}_3 = \kappa V(\phi) e^{2\alpha}. \quad (2.10d)
\]
From (2.10b), (2.10c) and (2.10d) follows
\[
\dot{\beta}_1 = \dot{\beta}_2 = \dot{\beta}_3. \quad (2.11)
\]
On account of coordinate condition (2.3) we then find
\[
\beta_1 = (\alpha + c_1 t)/3, \quad \beta_2 = (\alpha + c_2 t)/3, \quad \beta_3 = (\alpha + c_3 t)/3, \quad (2.12)
\]
with \( C_i \) being the integration constants, obeying
\[
c_1 + c_2 + c_3 = 0. \quad (2.13)
\]
From (2.13) it follows that in case of \( c_1 = c_2 = c_3 = 0 \) the expansion process is isotropic for arbitrary \( \alpha(t) \), while in case of nontrivial \( C_i \)'s the expansion is isotropic only if \( \alpha(t) \sim t^p \) with \( p > 1 \) as \( t \to \infty \).

Let us consider the field equations. Summation of (2.10b), (2.10c) and (2.10d), on account of coordinate condition gives
\[
\ddot{\alpha} = 3 \kappa V(\phi) e^{2\alpha}. \quad (2.14)
\]
From (2.10a) in view of (2.12), (2.13) and (2.14) one finds
\[
\alpha^2 - N^2 = 3 \kappa \left( \frac{1}{2} \dot{\phi}^2 + V(\phi) e^{2\alpha} \right), \quad N^2 = \frac{1}{6} \left( c_1^2 + c_2^2 + c_3^2 \right). \quad (2.15)
\]
Thus we have three equations (2.14), (2.15) and (2.8) for defining \( \alpha \) and \( \varphi \).

We are now in a position where two possible strategies could be exploited. According to the first one we seek the solutions \( \alpha(t) \) and \( \varphi(t) \) to the equations (2.14), (2.15) and (2.8) for a given potential \( V(\phi) \). It is known as direct problem. Following the second strategy, we invert the problem and construct the effective potential \( V(\phi) \), hence the scalar field \( \varphi(t) \) by choosing the appropriate metric function \( \alpha(t) \) [37]. This is known as inverse problem. We study both direct and inverse problem in the following sections.

### III. DIRECT PROBLEM

In this section we study the direct problem solving the equations (2.14), (2.15), (2.8) to define \( \alpha(t) \) and \( \varphi(t) \) for a given potential \( V(\phi) \). Since the present day Universe is surprisingly isotropic,
our main objective will be to define potential that leads to isotropization of the initially anisotropic space-time.

Let us choose the potential in the form:

$$V(\phi) = V_0 e^{\lambda \phi(t)}, \quad \lambda = \text{const.} \quad (3.1)$$

The corresponding equations now take the form

$$\ddot{\alpha} = 3 \kappa V_0 e^{\lambda \phi + 2\alpha}, \quad (3.2)$$

$$\alpha^2 - N^2 = 3 \kappa \left(\frac{1}{2} \phi^2 + V_0 e^{\lambda \phi + 2\alpha}\right), \quad (3.3)$$

$$\dot{\phi} = -\lambda V_0 e^{\lambda \phi + 2\alpha}. \quad (3.4)$$

Equations (3.2) and (3.4) leads to

$$\lambda \ddot{\alpha} + 3 \kappa \dot{\phi} = 0, \quad (3.5)$$

with the solution

$$\lambda \alpha + 3 \kappa \phi = A_1 t, \quad A_1 = \text{const.} \quad (3.6)$$

Inserting $\phi$ from (3.6) into (3.2) we find

$$\ddot{\alpha} = 3 \kappa V_0 e^{\alpha(t)} \frac{a(6 \kappa - \lambda^2)}{3 \kappa} + A_1 t, \quad A_1 = \frac{\lambda A_1}{3 \kappa}. \quad (3.7)$$

Depending on $6 \kappa - \lambda^2$ there occurs three possibilities.

**Case I**

Let us consider the case with $6 \kappa - \lambda^2 = p_1^2 > 0$. Introducing

$$\eta(t) = \frac{p_1^2}{3 \kappa} \alpha + A_1 t, \quad (3.8)$$

from (3.7) one finds

$$\dot{\eta} = p_1^2 V_0 e^{\eta}. \quad (3.9)$$

Solving the Eq. (3.9) we obtain

$$e^{\eta} = \frac{c_4}{2 p_1^2 V_0} \frac{1}{\sinh \left(\sqrt{c_4 t}/2\right)}. \quad (3.10)$$

Inserting (3.10) into (3.8) we find

$$\alpha(t) = \frac{3 \kappa}{p_1^2} \left[ \ln \left(c_4/2 p_1^2 V_0\right) - 2 \ln \left[\sinh \left(\sqrt{c_4 t}/2\right)\right] - A_1 t \right]. \quad (3.11)$$

As one sees, $\alpha$ is a linear function of $t$. Thus we conclude that in case of $6 \kappa - \lambda^2 = p_1^2 > 0$ the metric coefficients are the linear functions of $t$ and in this case no isotropization process takes place.

**Case II**
Let us consider the case with $6\kappa - \lambda^2 = -p_2^2 < 0$. Introducing

$$\xi(t) = -\frac{p_2^2}{3\kappa}\alpha + At, \quad (3.12)$$

from (3.7) one finds

$$\ddot{\xi} = -\frac{p_2^2}{V_0}e^{\xi}. \quad (3.13)$$

The Eq. (3.13) has the following solution

$$e^\xi = \frac{c_4}{2p_2^2V_0\cosh(\sqrt{c_4}t/2)}. \quad (3.14)$$

Inserting (3.14) into (3.12) one gets

$$\alpha(t) = -\frac{3\kappa}{p_2^2}\left[\ln\left(\frac{c_4}{2p_2^2V_0}\right) - 2\ln[\cosh(\sqrt{c_4}t/2)] - At\right]. \quad (3.15)$$

As one sees, $\alpha$ is a linear function of $t$. In means, as in case I, the assumption $6\kappa - \lambda^2 = -p_2^2 < 0$ leads to the metric coefficients be the linear functions of $t$ and in the case in hand no isotropization process takes place.

**Case III**

Let us consider the case with $(6\kappa - \lambda^2) = 0$. We will study the partial case setting $A_1 = 0$. Then for $\alpha$ and $\phi$ we have

$$\dot{\alpha} = 3\kappa V_0, \quad \Rightarrow \quad \alpha = \frac{3\kappa V_0}{2}t^2 + c_5t + c_{50}, \quad (3.16)$$

$$\dot{\phi} = -\lambda V_0, \quad \Rightarrow \quad \phi = -\frac{\lambda V_0}{2}t^2 + c_6t + c_{60}. \quad (3.17)$$

Thus we see that for $\lambda = \pm\sqrt{6\kappa}$, $\alpha$ is a quadratic function of $t$, which allows isotropic expansion of the Universe. This result is in agreement with (4.13). Hence, for $n = 0$, only the potential of type (4.13) leads to isotropization.

**IV. INVERSE PROBLEM**

In this section we study the inverse problem. Here we seek the potential for the given metric functions $\alpha$ and scalar field $\phi$. As some special cases we look for the potentials leading to the isotropization of initially anisotropic metric and inflationary scenario.

Let us first study the inverse problem in general. In doing so we assume

$$\alpha(t) = \Gamma[\phi(t)]. \quad (4.1)$$

Inserting (4.1) into (2.15) we find

$$\phi^2 = \frac{N^2 + 3\kappa V(\phi)e^{2\Gamma}}{\Gamma_\phi^2 - 3\kappa/2}, \quad \Gamma_\phi = \frac{d\Gamma}{d\phi}. \quad (4.2)$$
Differentiation of (4.2) with respect to $t$ on account of (2.8) gives
\[ V_\varphi + M(\varphi)V + H(\varphi) = 0, \] (4.3)
with
\[ M(\varphi) = \frac{3 \varphi}{\Gamma_\varphi} \left( 1 - \frac{\Gamma_{\varphi\varphi}}{\Gamma_\varphi^2 - 3 \varphi/2} \right), \quad H(\varphi) = -N^2 \frac{e^{-2\Gamma}}{\Gamma_\varphi^2 - 3 \varphi/2} \Gamma_{\varphi\varphi}. \] (4.4)

The equation (4.3) is the first order linear inhomogeneous equation with the general solution
\[ V(\varphi) = e^{-\int M d\varphi} \left[ c_4 - \int d\varphi H(\varphi) e^{\int M d\varphi} \right], \quad c_4 = \text{const.}, \] (4.5)
which can be viewed as equation for defining $V(\varphi)$ for a given metric function $\Gamma(\varphi)$. In what follows we find the potentials $V(\varphi)$ leading to some specific cosmological solutions.

### A. Potential for isotropization

In this subsection we looking for the potentials leading to the isotropization of initially anisotropic metric. In doing so we consider two cases.

#### 1. Asymptotically isotropic space-time

Let us find potential that leads to the asymptotic isotropization of the initially anisotropic model. Note that the space-time becomes asymptotically isotropic if:
\[ \alpha(t) \big|_{t \to \infty} \propto \alpha_0 t^p, \quad p > 1, \quad \alpha_0 = \text{const.} \] (4.6)

Inserting $\alpha(t)$ from (4.6) into (2.14) one finds
\[ \alpha_0 p(p - 1) t^{2p - 2} = 3 \varphi V(\varphi) e^{2\alpha_0 t^p}. \] (4.7)

Further inserting $\alpha(t)$ into (2.15) on account of (4.7) we have
\[ \alpha_0^2 p^2 t^{2p - 2} - N^2 = \frac{3 \varphi}{2} \varphi^2 + \alpha_0 p(p - 1) t^{p - 2}. \] (4.8)

From (4.8) one finds
\[ \varphi(t) \big|_{t \to \infty} = \pm \alpha_0 \sqrt{\frac{2}{3 \varphi}} t^p = \pm \sqrt{\frac{2}{3 \varphi}} \alpha(t). \] (4.9)

From (4.9) one finds
\[ t = \left( \pm \frac{1}{\alpha_0} \sqrt{\frac{3 \varphi}{2}} \varphi(t) \right)^{1/p}. \] (4.10)

Inserting $t$ from (4.10) into (4.7) one finds
\[ 3 \varphi V(\varphi) = \alpha_0 p(p - 1) \left( \pm \frac{1}{\alpha_0} \sqrt{\frac{3 \varphi}{2}} \varphi(t) \right)^{(p - 2)/p} e^{\pm 2 \sqrt{3 \varphi} \varphi(t)}. \] (4.11)
The general form of potential, leading to isotropization, is:

\[ V(\varphi) = V_0 \varphi^n e^{-\frac{n}{2} \varphi(t)} , \quad n = \frac{p-2}{p} , \quad p > 1 , \quad -1 < n < 1. \] (4.12)

The simplest form of scalar field potential is obtained for \( p = 2, n = 0 \):

\[ V(\varphi) = V_0 e^{-\frac{1}{2} \varphi(t)} . \] (4.13)

Thus we find that the potential given by (4.13) leads to the asymptotic isotropization of initially anisotropic space-time.

2. Isotropic space-time

Let us consider the isotropic model when \( \beta_1(t) = \beta_2(t) = \beta_3(t) = \alpha(t)/3 \), i.e., \( c_1 = c_2 = c_3 = 0 \) in (2.12). It means \( N^2 = 0 \) in (2.15) and \( H(\varphi) = 0 \) in (4.3). The metric and basic system of equations in this case takes the form:

\[ ds^2 = e^{2\alpha} dt^2 - e^{2\alpha/3} (dx^2 + dy^2 + dz^2) . \] (4.14)

\[ \ddot{\alpha} = 3\kappa V(\varphi)e^{2\alpha} , \] (4.15)

\[ \dot{\alpha}^2 = 3\kappa \left( \frac{1}{2} \dot{\varphi}^2 + V(\varphi)e^{2\alpha} \right) , \] (4.16)

\[ \ddot{\varphi} = -\frac{dV(\varphi)}{d\varphi} e^{2\alpha} . \] (4.17)

In this case from (4.3) we find

\[ V(\varphi) = c_4 \left( \frac{3\kappa}{2} \frac{1}{\Gamma_{\varphi}^3} - 1 \right) e^{3\kappa \int \frac{d\varphi}{\Gamma_{\varphi}}} , \quad \Gamma(\varphi) = \alpha(t) , \quad \Gamma_{\varphi} = \frac{d\Gamma}{d\varphi} . \] (4.18)

For \( \Gamma(\varphi) \) from (4.3) we find

\[ \Gamma_{\varphi\varphi} - \frac{1}{3\kappa} \frac{V_{\varphi}}{V} \Gamma_{\varphi}^3 - \Gamma_{\varphi}^2 - \frac{1}{2} \frac{V_{\varphi}}{V} \Gamma_{\varphi} + \frac{3\kappa}{2} = 0 . \] (4.19)

It is the Abel equation of first kind.

Introducing a new function

\[ U(\psi) = e^{\frac{3\kappa}{2} \int \frac{d\varphi}{\Gamma_{\varphi}}} , \quad \psi = \sqrt{3\kappa} \varphi , \] (4.20)

from (4.18) we find

\[ \frac{V}{c_4} = U'' - U^2 , \quad U' = \frac{dU}{d\psi} . \] (4.21)

The equation (4.21) possesses exact solution for some \( V(\varphi) \). Some simple cases are

\[ V = c_4 \cos 2\psi \quad \Rightarrow \quad U = \sin \psi , \] (4.22)

\[ V = 0 \quad \Rightarrow \quad U = \exp \psi , \] (4.23)

\[ V = c_4 \quad \Rightarrow \quad U = \sinh \psi . \] (4.24)
B. Potential for inflation

Let us define the scalar field potential leading to inflation. The isotropic model of the Universe in harmonic time is given by the metric
\[
ds^2 = e^{2\alpha(t)} dt^2 - e^{2\alpha(t)} (dx^2 + dy^2 + dz^2),
\]
which in proper synchronic time takes the form
\[
ds^2 = d\tau^2 - a^2(\tau) (dx^2 + dy^2 + dz^2).
\]
In inflation regime \(a(\tau) \sim t^p, \ p > 1\). Comparing (4.25) and (4.26) one finds
\[
d\tau = \pm e^{\alpha(t)} dt, \quad \Rightarrow \quad \dot{\tau} = \pm \int e^{\alpha(t)} dt, \quad (4.27)
\]
For inflation regime the function \(\tau(t)\) is determined from (4.28) for the given \(a(\tau)\). From (4.27) we have \(\pm \alpha(t) = \ln \dot{\tau}\). Defining \(\dot{\tau}\) for the given \(a(\tau)\) from (4.28) one finds \(\alpha(t)\). Further inserting \(\alpha(t)\) into (4.15) and (4.16) we find \(\phi(t)\) and \(V(\phi)\), i.e., potential that leads to inflation. In this regime
\[
a(\tau) = (H\tau)^p, \quad H = \text{const.}, \quad p = \text{const.} > 1.
\]
In this case from (4.28) follows
\[
\int (H\tau)^{-3p} d\tau = \frac{1}{H} \frac{(H\tau)^{1-3p}}{1-3p} = t, \quad (4.30)
\]
that gives
\[
\tau(t) = \frac{1}{H} (AHt)^{1/A}, \quad e^{\alpha(t)} = \tau = (AHt)^B, \quad A = 1 - 3p < 0, \quad B = \frac{1}{A} - 1.
\]
After a little manipulation one finds
\[
\phi(t) = \pm \mathcal{D} \ln |t|, \quad \mathcal{D} = \sqrt{\frac{2}{3\mathcal{A}}} B(B+1),
\]
and
\[
V(\phi) = V_0 e^{\pm \sqrt{2\mathcal{A}/p} \phi}.
\]
Thus we found \(V(\phi)\) in harmonic coordinates, leading to the power law expansion in proper synchronic time. \(V(\phi) \rightarrow \text{const. as } p \rightarrow \infty\), which corresponds to the cosmological constant.

C. Power law expansion

Finally, we define the scalar field potential leading to the power law expansion in the proper synchronic time. The initial metric in this case takes the form (4.26). In this case \(a(\tau)\) is given by (4.29) with \(p\) being arbitrary constant. The Einstein equation for (4.26) takes the form
\[
3 \frac{d^2 x}{d\tau^2} = \mathcal{A} \mathcal{I}_0^0 = \mathcal{A} \left[ \frac{1}{2} \phi^2 + V(\phi) \right], \quad (4.34)
\]
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\[ 2\ddot{a} + \frac{\dot{a}^2}{a^2} = \kappa T^i_i = \kappa \left[ -\frac{1}{2} \Phi^2 + V(\Phi) \right]. \] (4.35)

Subtraction (4.35) from (4.34) on account (4.29) gives

\[ \Phi = \pm \sqrt{\frac{2p}{\kappa}} (\ln \tau + \ln \tau_0), \quad \Rightarrow \quad \tau = \tau_0 e^{\pm \sqrt{\frac{2p}{\kappa}} \Phi}. \] (4.36)

Summation of (4.35) and (4.34) in this case gives

\[ V(\Phi) = V_0 e^{\pm \sqrt{\frac{2p}{\kappa}} \Phi}, \quad V_0 = \frac{p(3p - 1)}{\kappa \tau^2_0}, \] (4.37)

which coincides with that of (4.33).

V. CONCLUSION

The general form of scalar field potentials leading to the asymptotic isotropization in case of Bianchi type-I cosmological model, and inflationary regime in case of isotropic space-time is obtained. In doing so we solved both direct and inverse problem. The scalar field potentials leading to the inflation and isotropization were found both for harmonic and proper synchronic time. It is shown that in the cases considered, the potential that leads to isotropization takes the form \( V(\Phi) = V_0 \Phi^n e^{\pm \sqrt{6p} \Phi} \), with \( n \in (-1, +1) \) being some constant. In case of \( n = 0 \) we find \( V(\Phi) = V_0 e^{\pm \sqrt{6p} \Phi} \). The last one leads to inflation as well.

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