

BIANCHI TYPE-III COSMIC STRINGS AND DOMAIN WALLS IN $f(R, T)$ GRAVITY

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ABSTRACT. In this paper, we have considered Bianchi type-III space time in the presence of cosmic strings and domain walls within the framework of $f(R, T)$ gravity formulated by Harko et al. (Phys. Rev. D, 84: 024020, 2011). To obtain the exact solution of the corresponding cosmological model, we assume the condition that the shear scalar is directly proportional to the scalar expansion of the space-time and special law of variation for Hubble's parameter proposed by Berman (Nuovo Ciment B, 74:182, 1983). Some physical and kinematical properties of the models are also discussed.

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Keywords: Bianchi type-III; Cosmic strings; Domain walls; $f(R, T)$ gravity.

1. INTRODUCTION

It is well known that the discovery of the modern cosmology is that the current universe is not only expanding but also accelerating. This late time accelerated expansion of the universe has been confirmed by the high red-shift supernovae experiments (Riess et al. [27], Perlmutter et al. [21], Bennet et al. [3]) and also by

some observations such as cosmic microwave background (CMB) radiation (Spergel et al. [33,34]), baryon acoustics oscillations [11], large scale structure (LSS) [35]. These observations led to so many ideas and changed the concept of matter-energy composition of the universe. In view of this, it is now believed that the matter-energy composition of universe has 4% ordinary matter, 20% dark matter and 76% dark energy (DE) amongst which dark energy is one of the main components which is responsible for this cosmic acceleration of the universe. The negative pressure (i.e. positive energy density) has sufficient power to work against gravity and it may provides the accelerated expansion of the universe. Though the dark energy is said to be a main cause for cosmic acceleration issue, its nature is still challenging. Moreover from time to time many candidates have been proposed to address this particular issue. The cosmological constant λ or the vacuum energy is the most simple and natural candidate for DE, which appears to fit the observational data. However, despite of its success the λ -cold dark matter (λ -CDM) model faces serious time tuning and coincidence problems. In order to understand the exotic nature of dark energy and the consequent late time cosmic acceleration of the universe, in recent years two different approaches in general relativity have gained more importance. General relativity (GR) can be modified in two different ways: either the matter source can be modified or the underlying geometry can be modified. The later approach has attracted more and more attention, in recent years, where the standard Einstein-Hilbert action of GR is replaced by an arbitrary function may be of Ricci Scalar R ($f(R)$ gravity), of Scalar Tension T ($f(T)$ gravity), of G ($f(G)$ gravity) and $f(R, G)$ gravity or of inclusion of some other matter field lagrangian L_m along with some geometrical features. Very recently, Harko et al. [14] have proposed a modified $f(R, T)$ theory of gravity where in the gravitational Lagrangian L_m is given by an arbitrary function of the Ricci scalar R and of the trace T of the stress-energy tensor. The gravitational field equations have been derived from the Hilbert-Einstein type variational principle by taking the action

$$(1) \quad S = \frac{1}{16\pi} \int f(R, T) \sqrt{-g} d^4x + \int L_m \sqrt{-g} d^4x.$$

Here $f(R, T)$ is an arbitrary function of the Ricci scalar R , T is the trace of energy momentum tensor of the matter T_{ij} , L_m is the matter Lagrangian.

The stress-energy momentum tensor of matter and its trace T are given by

$$(2) \quad T_{ij} = -\frac{2}{\sqrt{-g}} \frac{\delta(\sqrt{-g}L_m)}{\delta g^{ij}} \quad \text{and} \quad T = g^{ij}T_{ij}.$$

By assuming that L_m of matter depends only on the metric tensor components g_{ij} rather than its derivatives, we obtain

$$(3) \quad T_{ij} = g_{ij}L_m - 2\frac{\partial L_m}{\partial g^{ij}}.$$

Now by varying the action S of the gravitational field with respect to the metric tensor component g^{ij} , we obtain the field equations of $f(R, T)$ gravity as

$$(4) \quad \begin{aligned} f(R, T)R_{ij} - \frac{1}{2}f(R, T)g_{ij} + (g_{ij}\square - \nabla_i\nabla_j)f_R(R, T) \\ = 8\pi T_{ij} - f_T(R, T)T_{ij} - f_T(R, T)\theta_{ij}, \end{aligned}$$

where

$$(5) \quad \theta_{ij} = -2T_{ij} + g_{ij}L_m - 2g^{lk}\frac{\partial^2 L_m}{\partial g^{ij}\partial g^{lm}}.$$

Here $f_R = \frac{\partial f(R, T)}{\partial R}$, $f_T = \frac{\partial f(R, T)}{\partial T}$, $\square = \nabla^i\nabla_i$, ∇_i is the covariant derivative. Also T_{ij} is the standard matter-energy momentum tensor derived from Lagrangian L_m . It may be noted that when $f(R, T) \equiv f(R)$, the equations (4) yield the field equations of $f(R)$ gravity.

The perfect fluid form of the stress-energy tensor of the matter Lagrangian is given by

$$(6) \quad T_{ij} = (\rho + p)u_i u_j - pg_{ij},$$

where $u^i = (1, 0, 0, 0)$ is the four-velocity vector which satisfies the condition $u^i u_i = 1$ and $u^i \nabla_j u_i = 0$. Here ρ and p are energy density and pressure of the fluid respectively.

From equation (5) the variation of stress-energy of perfect fluid is given by the expression

$$(7) \quad \theta_{ij} = -2T_{ij} - pg_{ij}.$$

It must be noted that the field equations also depend through the tensor θ_{ij} , on the physics nature of the matter field. Hence in case of $f(R, T)$ gravity depending

on the nature of the matter source, for each choice of $f(R, T)$, we obtain different theoretical models. Assuming

$$(8) \quad f(R, T) = R + 2f(T)$$

as a first choice, where $f(T)$ is an arbitrary function of the trace of stress-energy tensor of matter, from equation (4) we obtain the gravitational field equations of $f(R, T)$ gravity as

$$(9) \quad R_{ij} - \frac{1}{2}Rg_{ij} = 8\pi T_{ij} - 2f'(T)T_{ij} - 2f'(T)\theta_{ij} + f(T)g_{ij},$$

where the overhead prime denotes derivative with respect to the argument.

If the matter source is a perfect fluid $\theta_{ij} = -2T_{ij} - pg_{ij}$, then the field equations (9) take the form

$$(10) \quad R_{ij} - \frac{1}{2}Rg_{ij} = 8\pi T_{ij} + 2f'(T)T_{ij} + [2pf'(T) + f(T)]g_{ij}.$$

Harko et al. [14] have discussed several aspects of $f(R, T)$ gravity. Dagwal and Pawar [6] have discussed cosmological model with EoS parameter in $f(T)$ theory of gravity. Adhav [1] studied LRS Bianchi type-I cosmological model in $f(R, T)$ theory of gravity. Dagwal and Pawar [7] have studied tilted cosmological models in $f(T)$ theory of gravity. Naidu et al. [19] have discussed Bianchi type-V bulk viscous string cosmological model in $f(R, T)$ gravity. Singh and Sharma [31] have discussed Bianchi-type-II dark energy model in $f(R, T)$ gravity. Dagwal and Pawar [10] have discussed study of cosmic models in $f(R, T)$ gravity with tilted observers. Pawar and Solanke [20] have studied cosmological models filled with a perfect fluid source in the $f(R, T)$ theory of gravity. Ram and Chandel [24] have obtained dynamics of magnetized string cosmological model in $f(R, T)$ gravity theory. Sahoo [30] has investigated LRS Bianchi type-I string cosmological model in $f(R, T)$ gravity. Solanke et al. [32] have discussed accelerating dark energy universe with LRS Bianchi type-I space. Santhi et al. [28] have obtained interacting LRS Bianchi type-I cosmological model in $f(R, T)$ gravity with modified chaplygin gas. Dagwal and Pawar [8] have discussed two-fluid sources in $F(T)$ theory of gravity. Dagwal [9] has investigated Mesonic tilted cosmological model with wet dark fluid in $F(T)$ theory of gravity.

In addition to above, the study of cosmic strings and domain walls has received considerable attention in cosmology since it plays an important role in structure formation and evolution of the universe. Cosmic strings and domain walls are topological defects associated with spontaneous symmetry breaking whose plausible production site is cosmological phase transitions in the early universe. The gravitational effects of cosmic strings, both in general relativity and in the alternative have been extensively discussed by Vilenkin [38], Gott [13], Letelier [17], Satchel [29], Reddy [26], Venkateswarlu et al. [37] and Pradhan et al. [22]. In particular, the domain walls have become important in recent years from cosmological stand-point when a new scenario of galaxy formation has been proposed by Hillet et al. [15]. Vilenkin [39], Iser and Sikivie [16], Widrow [41], Goetz [12], Mukherjee [18], Wang [40], Adhav et al. [2], Rahaman et al. [23] are some of the authors who have investigated several aspects of domain walls. Reddy and Naidu [25] have discussed cosmic strings and domain walls in scale-covariant theory of gravitation and also Venkateswarlu and Sreenivas [36] have investigated axially symmetric domain walls and cosmic strings in modified theory of gravitation.

Motivated by the above discussion and investigations, in this paper, we investigate Bianchi type-III cosmological model in presence of cosmic strings and domain walls in the framework of $f(R, T)$ gravity proposed by Harko et al. [14]

2. METRIC AND FIELD EQUATIONS

We consider Bianchi type-III metric in the form

$$(11) \quad ds^2 = dt^2 - A^2 dx^2 - B^2 e^{-2\alpha x} dy^2 - C^2 dz^2,$$

where A, B, C are function of cosmic time t and α is non-zero constant.

The energy momentum tensor T_{ij} for cosmic string is given by

$$(12) \quad T_{ij} = \rho u_i u_j - \lambda x_i x_j,$$

where ρ is the rest energy density of the cloud of strings with particles attached to them, λ is the tension density of the strings and $\rho = \rho_p + \lambda$, ρ_p being the energy density of the particles. u^i describes the cloud four velocity and x^i represents the direction of strings, which will satisfy

$$(13) \quad u^i u_i = -x^i x_i = 1 \text{ and } u^i x_i = 0.$$

In the co-moving coordinate system, taking the string in z-direction, equation (12) gives

$$(14) \quad T_1^1 = 0, \quad T_2^2 = 0, \quad T_3^3 = \lambda, \quad T_4^4 = \rho.$$

quantities ρ and λ depend on t .

Considering the function $f(T) = \mu T$ and $f'(T) = \mu$, where μ is a constant, the $f(R, T)$ gravity field equations (10) with the help of (14) for metric (11) are

$$(15) \quad \frac{\ddot{B}}{B} + \frac{\dot{B}\dot{C}}{BC} + \frac{\ddot{C}}{C} = -[2p\mu + \mu(\rho + \lambda)],$$

$$(16) \quad \frac{\ddot{A}}{A} + \frac{\ddot{C}}{C} + \frac{\dot{A}\dot{C}}{AC} = -[2p\mu + \mu(\rho + \lambda)],$$

$$(17) \quad \frac{\ddot{A}}{A} + \frac{\ddot{B}}{B} + \frac{\dot{A}\dot{B}}{AB} - \frac{\alpha^2}{A^2} = -[(8\pi + 2\mu)\lambda + 2p\mu + \mu(\rho + \lambda)],$$

$$(18) \quad \frac{\dot{A}\dot{B}}{AB} + \frac{\dot{A}\dot{C}}{AC} + \frac{\dot{B}\dot{C}}{BC} - \frac{\alpha^2}{A^2} = -[(8\pi + 2\mu)\rho + 2p\mu + \mu(\rho + \lambda)],$$

$$(19) \quad \frac{\dot{A}}{A} - \frac{\dot{B}}{B} = 0,$$

where an overhead dot indicates differentiation with respect to t . The trace in the considered model is given by $T = \rho + \lambda$.

On integrating equation (19), we obtain $B = kA$ where k is a constant of integration. Without loss of any generality for its value as unity, it become

$$(20) \quad B = A.$$

Using the relation (20), the field equations (15)-(18) reduce to the following system of independent equations

$$(21) \quad \frac{\ddot{A}}{A} + \left(\frac{\dot{A}}{A}\right)^2 - \frac{\dot{A}\dot{C}}{AC} - \frac{\ddot{C}}{C} - \frac{\alpha^2}{A^2} = -[(8\pi + 2\mu)\lambda]$$

$$(22) \quad \left(\frac{\dot{A}}{A}\right)^2 + \frac{\dot{A}\dot{C}}{AC} - \frac{\ddot{A}}{A} - \frac{\ddot{C}}{C} - \frac{\alpha^2}{A^2} = -[(8\pi + 2\mu)\rho].$$

3. SOLUTIONS AND THE COSMIC STRING MODEL

The field equations (21)–(22) are system of two independent equations in four unknowns A, C, ρ and λ . In order to get a deterministic solution, we take the help of following physically plausible conditions:

(i) The shear scalar σ is proportional to expansion scalar θ which leads to a relation between metric potential (Collins et. al. [5])

$$(23) \quad A = C^m, \text{ where } m \text{ is a non zero constant.}$$

(ii) Special law of variation of Hubble's parameter proposed by Berman [4], that yield constant deceleration parameter model of the universe and which is defined by

$$(24) \quad q = -\frac{R\ddot{R}}{\dot{R}^2} = \text{constant}, \text{ (Here } R \text{ is the scale factor.)},$$

which admits the solution

$$(25) \quad R = (ABC)^{\frac{1}{3}} = (at + b)^{\frac{1}{1+q}},$$

where $a \neq 0$ and b are constants of integration.

This equation shows that $1 + q > 0$ is the condition for accelerated expansion of the universe.

Using the above two conditions in the field equations (21) and (22), we obtain the expression for the metric potential as

$$(26) \quad A = B = (at + b)^{\frac{3m}{(1+q)(2m+1)}},$$

$$(27) \quad C = (at + b)^{\frac{3}{(1+q)(2m+1)}}.$$

Therefore, the Bianchi type-III cosmological model corresponding to the above solutions in $f(R, T)$ gravity can be written as

$$(28) \quad ds^2 = dt^2 - (at + b)^{\frac{6m}{(1+q)(2m+1)}} dx^2 - (at + b)^{\frac{6m}{(1+q)(2m+1)}} e^{-2\alpha x} dy^2 - (at + b)^{\frac{6}{(1+q)(2m+1)}} dz^2.$$

4. PHYSICAL PROPERTIES OF THE STRING COSMOLOGICAL MODEL

The physical and kinematical parameters of observational interest which play a vital role in the discussion of cosmology are the spatial volume V , the expansion scalar θ , shear scalar σ^2 , Hubble's parameter H and the mean anisotropy parameter A_h which are defined as

The spatial volume V is

$$(29) \quad V = (at + b)^{\frac{3}{(1+q)}}.$$

The scalar expansion θ is

$$(30) \quad \theta = 2 \frac{\dot{A}}{A} + \frac{\dot{C}}{C} = \frac{3a}{(1+q)(at+b)}.$$

The shear scalar σ^2 is defined as

$$(31) \quad \sigma^2 = \frac{1}{3} \left[\frac{\dot{A}}{A} - \frac{\dot{C}}{C} \right]^2 = \frac{3a^2(m-1)^2}{(1+q)^2(2m+1)^2(at+b)^2}.$$

The generalized mean Hubble parameter H is given in the form

$$(32) \quad H = \frac{1}{3}\theta = \frac{a}{(1+q)(at+b)}.$$

The mean anisotropy parameter is

$$(33) \quad A_h = \frac{2(m-1)^2}{(2m+1)^2}.$$

Also, the energy density is

$$(34) \quad \rho = \frac{1}{(8\pi + 2\mu)} \left[\frac{9a^2(1-m) - 3a^2(m+1)(1+q)(2m+1)}{(2m+1)^2(1+q)^2(at+b)^2} + \frac{\alpha^2}{(at+b)^{\frac{6m}{(2m+1)(1+q)}}} \right].$$

and the string tension density is given by

$$(35) \quad \lambda = \frac{1}{(8\pi + 2\mu)} \left[\frac{3a^2(2m+1)(1+q)(m-1) - 9a^2(2m^2 - m - 1)}{(2m+1)^2(1+q)^2(at+b)^2} + \frac{\alpha^2}{(at+b)^{\frac{6m}{(2m+1)(1+q)}}} \right].$$

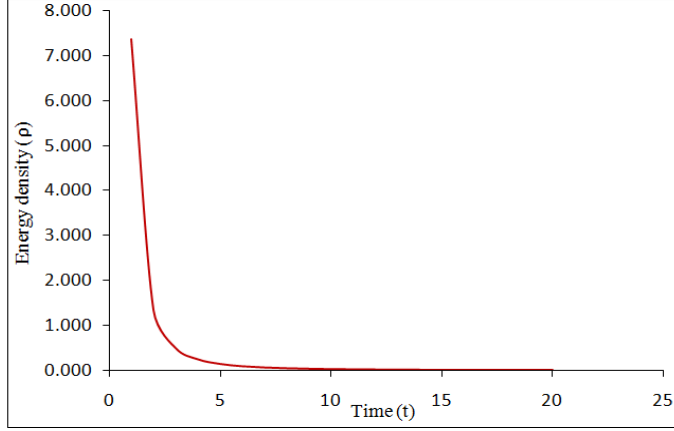


FIGURE 1. The plot of energy density ρ verses time t , $q = -0.1, m = 1.4, \mu = 1.5, \alpha = 2, a = 0.2$.

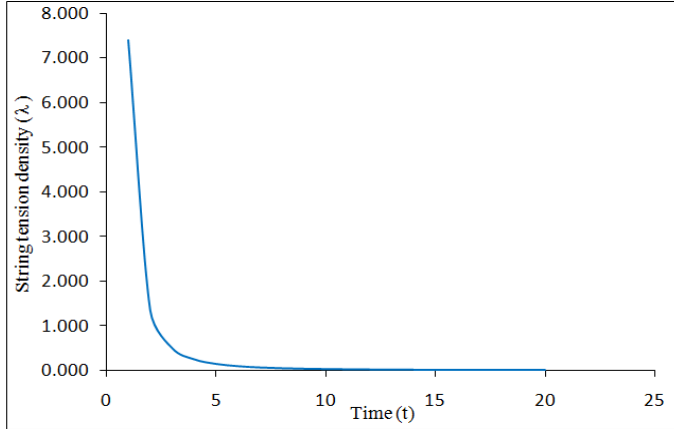


FIGURE 2. The plot of string tension density λ verses time t , $q = -0.1, m = 1.4, \mu = 1.5, \alpha = 2, a = 0.2$.

In Figs. 1 and 2, we plot energy density ρ and string tension density λ verses time t for $q = -0.1$. Here we noticed that ρ and λ are decreasing functions of time and approaches to zero as $t \rightarrow \infty$.

It is observed that model (28) has no initial singularity, i.e. at $t = 0$. The spatial volume V increases with cosmic time showing the late time accelerated expansion of the universe. The kinematical parameters scalar expansion θ , shear scalar σ^2 , Hubble parameter H are decreasing functions of time and approaches to zero as $t \rightarrow \infty$. Also the physical parameters energy density ρ and string tension density λ are decreasing functions of time

and approaches to zero as $t \rightarrow \infty$. Since $A_h \neq 0$ and $\frac{\sigma^2}{\theta^2} \neq 0$, the model is anisotropy throughout the evolution of the universe.

5. DOMAIN WALLS

The energy momentum tensor for domain walls is given by

$$(36) \quad T_{ij} = \rho(g_{ij} + \omega_i \omega_j) + p g_{ij}$$

where ρ is the energy density p stands for pressure, and ω^i is the four-velocity vector satisfying $\omega_i \omega^i = -1$. In the comoving co-ordinate system, we have from (36)

$$(37) \quad T_1^1 = T_2^2 = T_4^4 = \rho, \quad T_3^3 = -p \quad \text{and} \quad T_j^i = 0 \text{ for } i \neq j.$$

Now the field equations (10) of $f(R, T)$ gravity with the help of equations (36) and (37) for the metric (11) reduce to the following independent equations

$$(38) \quad \frac{\ddot{B}}{B} + \frac{\dot{B}\dot{C}}{BC} + \frac{\ddot{C}}{C} = -(8\pi + 5\mu)\rho - \mu p$$

$$(39) \quad \frac{\ddot{A}}{A} + \frac{\ddot{C}}{C} + \frac{\dot{A}\dot{C}}{AC} = -(8\pi + 5\mu)\rho - \mu p$$

$$(40) \quad \frac{\ddot{A}}{A} + \frac{\ddot{B}}{B} + \frac{\dot{A}\dot{B}}{AB} - \frac{\alpha^2}{A^2} = (8\pi + \mu)p - 3\mu\rho$$

$$(41) \quad \frac{\dot{A}\dot{B}}{AB} + \frac{\dot{A}\dot{C}}{AC} + \frac{\dot{B}\dot{C}}{BC} - \frac{\alpha^2}{A^2} = -(8\pi + 5\mu)\rho - \mu p$$

$$(42) \quad \frac{\dot{A}}{A} - \frac{\dot{B}}{B} = 0,$$

where the over dot indicates differentiation with respect to t .

The trace in the considered model is given by $T = T_1^1 + T_2^2 + T_3^3 + T_4^4 = 3\rho - p$.

On integrating equation (42), we obtain $B = kA$ where k is a constant of integration without loss of any generality for its value as unity, it become

$$(43) \quad B = A.$$

Using the relation (43), the field equations (38)-(41) reduce to the following system of independent equations

$$(44) \quad \frac{\ddot{A}}{A} + \frac{\ddot{C}}{C} + \frac{\dot{A}\dot{C}}{AC} = -(8\pi + 5\mu)\rho - \mu p$$

$$(45) \quad 2\frac{\ddot{A}}{A} + \left(\frac{\dot{A}}{A}\right)^2 - \frac{\alpha^2}{A^2} = (8\pi + \mu)p - 3\mu\rho$$

$$(46) \quad \left(\frac{\dot{A}}{A}\right)^2 + 2\frac{\dot{A}\dot{C}}{AC} - \frac{\alpha^2}{A^2} = -(8\pi + 5\mu)\rho - \mu p.$$

To obtain a determinate solution once again we use the conditions given by (23) and (24). Hence, the field equations (44)-(46) together with equations (23) and (24) admit the solutions

$$(47) \quad A = B = (at + b)^{\frac{3m}{(1+q)(2m+1)}},$$

$$(48) \quad C = (at + b)^{\frac{3}{(1+q)(2m+1)}}.$$

which are similar to the equations (26) and (27). Using these relations it is a simple matter to see that the field equations (44)-(46), again leads to the model given by equation (28) with

$$(49) \quad \rho = \frac{1}{(8\pi + 5\mu)(8\pi + \mu) + 3\mu^2} \times \left\{ \begin{aligned} &\mu \left[\frac{6a^2m(2m+1)(1+q) - 27m^2a^2}{(2m+1)^2(1+q)^2(at+b)^2} + \frac{\alpha^2}{(at+b)^{\frac{6m}{(2m+1)(1+q)}}} \right] \\ &+ (8\pi + \mu) \left[\frac{3a^2(2m+1)(1+q)(m+1) - 9a^2(m^2+m+1)}{(2m+1)^2(1+q)^2(at+b)^2} \right] \end{aligned} \right\}$$

$$\text{and } p = \frac{1}{(8\pi + 5\mu)(8\pi + \mu) + 3\mu^2} \times$$

$$(50) \quad \left\{ \begin{aligned} &(8\pi + 5\mu) \left[\frac{27m^2a^2 - 6ma^2(2m+1)(1+q)}{(2m+1)^2(1+q)^2(at+b)^2} - \frac{\alpha^2}{(at+b)^{\frac{6m}{(2m+1)(1+q)}}} \right] \\ &+ 3\mu \left[\frac{3a^2(2m+1)(1+q)(m+1) - 9a^2(m^2+m+1)}{(2m+1)^2(1+q)^2(at+b)^2} \right] \end{aligned} \right\}.$$

The graphical presentations of the density ρ and pressure p for the domain walls are as follows:

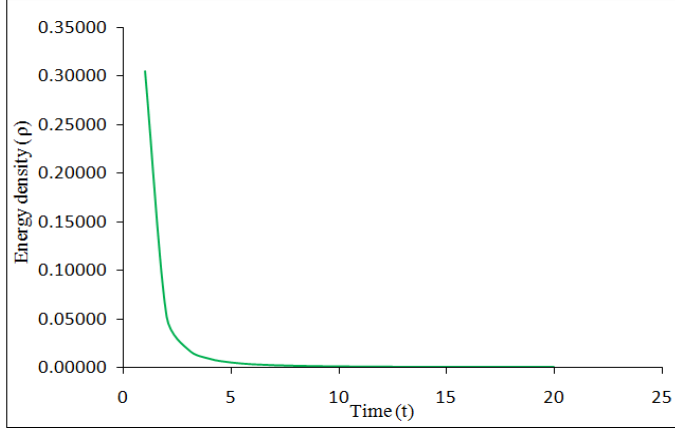


FIGURE 3. The plot of density ρ verses time t , $q = -0.1$, $m = 1.4$, $\mu = 1.5$, $\alpha = 2$, $a = 0.2$.

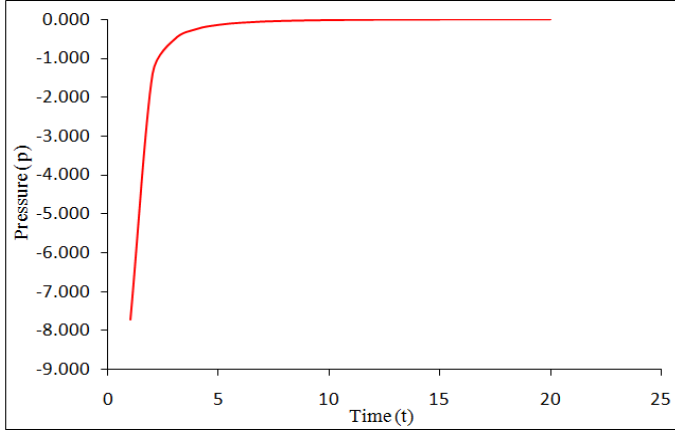


FIGURE 4. The plot of pressure p verses time t , $q = -0.1$, $m = 1.4$, $\mu = 1.5$, $\alpha = 2$, $a = 0.2$.

Figs. 3 and 4 represent the plot of density ρ and pressure p verses time t for $q = -0.1$. Here we observed that ρ and p are decreasing functions of time and approaches to zero as $t \rightarrow \infty$.

It is interesting to observed that in this case we obtain the same cosmological model given by equation (28) and all the properties are similar to that of Bianchi type-III cosmic string cosmological model as discussed in section-4 except the physical parameters ρ and p .

6. CONCLUSION

We have studied Bianchi type-III metric in presence of string and also domain walls source in modified $f(R, T)$ gravity formulated by Harko et al. [14]. It is observed that models have no initial singularity and show the late time accelerated expansion of the universe for large t . The kinematical parameters scalar expansion θ , shear scalar σ^2 , Hubble parameter H are decreasing functions of time and approaches to zero as $t \rightarrow \infty$. Also, the physical parameters energy density and string tension density decreases with increase in time and tends to zero as $t \rightarrow \infty$. The pressure increases exponentially negative initially and later approaches to zero with time t . Since $A_h \neq 0$ and $\frac{\sigma^2}{\theta^2} \neq 0$, the model is anisotropic throughout the evolution of universe. Thus, our model shows results comparable with the current observations of the universe.

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