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Research Article

PERFECT FLUID BIANCHI-III COSMOLOGICAL MODEL IN *f(R,T)* GRAVITY

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ABSTRACT

The spatially homogeneous & anisotropic Bianchi-III cosmological model in the presence of perfect fluid within the framework of $f(R,T)$ gravity is investigated. To get the exact solution of Einstein's field equations we have taken a special form of deceleration parameter and also used $C = V^b$ where C is metric coefficient, V is volume scale factor and b is any constant. The behavior of the important parameters like expansion scalar, shear scalar and average anisotropy parameter is discussed in detail.

INTRODUCTION

In today's scenario, the origin of our universe is one of the greatest cosmological mysteries. The actual physical situation of the formation of our universe at early stage is still unknown. But the different data from recent cosmological observations of type Ia supernovae (SNela) [1-4] have suggested that the current universe is undergoing in a phase of accelerated expansion. The explanation for this universe expansion has both theoretical as well as experimental background. It has been shown that most of the universe contains the dark energy with a negative pressure and occupies nearly 76% part of the universe. The vacuum energy density which is mathematically equivalent to the cosmological constant Λ, may be a suitable alternative for dark energy. Many researchers have been proposed a dark energy models to explain the cosmic accelerated expansion [5]. Recently Rao *et al*. [6] have studied the dark energy (DE) model with variable EoS parameter in the Seaz & Ballester scalar tensor theory of gravitation. Karami *et al*. [7] derived a polytrophic gas model of DE as an alternative model to explain the accelerated expansion of the universe. Gupta and Pradhan [8] proposed a new candidate knows as cosmological nuclear energy as a possible candidate for the dark energy.

During last decade, the modifications of general theory of relativity are attracting more attention to provide natural gravitational alternative way for dark energy. Among these modifications, $f(R)$ theory of gravity is one of the most attractive theory which is firstly proposed by Buchdahl [9] in 1970. This gravity has created a lot of interest in relativist. It has been suggested that the cosmic acceleration can be achieved by replacing the Einstein Hilbert action of GR with the general Ricci scalar R. This theory is helpful to explain early time inflation and late time acceleration of the universe. Nojiri and Odinstov [10,11] indicated that the modified theories of gravity provide a natural gravitational alternative to dark energy. Carroll *et al.* [12] presented the late time acceleration of the universe in $f(R)$ gravity.

Many researchers have studied $f(R)$ gravity in several contexts and tried to find analytical solutions for the unknown functional form $f(R)$. For example, Sharif and Shamir [13, 14] have studied the vacuum & non-vacuum solutions of Bianchi Type– I and V in $f(R)$ gravity by using the law of variation of Hubble parameter. Also, Shamir [15] have presented the plane symmetric vacuum

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solution of Bianchi Type-III space time in $f(R)$ gravity. The spherically symmetric vacuum solutions in $f(R)$ gravity have been obtained by Multamaki and Vilja [16]. Capozziello *et al.* [17] derived the spherically symmetric solutions of $f(R)$ theory of gravity via the Noether symmetry approach. In $f(R)$ gravity Sebastini and Zerbini [18] have studied the non constant curvature vacuum solutions for the static spherically symmetric in $f(R)$ gravity. Adhav [19, 20] has investigated the Bianchi type-II cosmological model with perfect fluid and Kantowski Sachs string cosmological model in $f(R)$ gravity. The cylindrical symmetric vacuum solutions has explored by Azadi *et al.* [21] in $f(R)$ gravity. Recentely, exact vacuum solutions of five dimensional Bianchi type-V space-time in $f(R)$ theory of gravity studied by Hiwarkar [22]. Non-vacuum solutions of five dimensional Bianchi type-I space-time in $f(R)$ theory of gravity obtained by Hiwarkar [23].

Recently, Harko *et al.* [24] have developed the another interesting and prospective of General theory of relativity, called $f(R,T)$ modified theory of gravity where the gravitational Lagrangian given in terms of an arbitrary function of Ricci scalar R and the trace T of the energy momentum tensor T_{ij} .They have constructed different cosmological models using three explicit forms of $f(R,T)$ .Recently some authors (Ahmad and Pradhan [25], Naidu [26], Yadav [27], Shriram *et al.*[28]) have obtained anisotropic cosmological model in $f(R,T)$ gravity theory. Adhav [29] has developed LRS Bianchi Type-I cosmological model with perfect fluid in $f(R,T)$ gravity. Choubey and Shukla [30] have investigated the new class of Bianchi Types-III,V, VI_0 models in the presence of perfect fluid in $f(R,T)$ theory of gravity. The perfect fluid solutions of Bianchi type-I space time in scalar tensor theory have been explored by Kumar and Singh [31].Currently, Ladke *et. al.* [32] have constructed the higher dimensional Bianchi-I cosmological model in $f(R,T)$ theory of gravitation.

The investigation of Bianchi type models in modified theories of gravity play a vital role in describing the large scale behavior of the universe. Motivated by the above investigation, in this paper we have explored Bianchi-III cosmological model filled with the perfect fluid by assuming the special form of deceleration parameter and taking $C = V^b$, where C is a metric coefficient, V is a volume scale factor and b is any constant. This paper organized as follows: In section (2), we consider the Bianchi Type-III space time and developed a Einstein's field equations in $f(R,T)$ theory of gravity. Sections (3) and (4) is used to find solution of anisotropic Bianchi Type-III space time filled with perfect fluid along with some physical quantities. In last section we discuss the conclusion.

Metric and f(R,T) theory of gravity

We consider the line element of Bianchi type-III space-time and is given by

$$ds^2 = dt^2 - A^2dx^2 - B^2e^{-2\alpha x}dy^2 - C^2dz^2, \tag{1}$$

where A, B and C are metric coefficients and functions of cosmic time t, $\alpha \neq 0$ is a positive constant.
The $f(R,T)$ theory of gravity is the generalization of General Relativity. In this theory, the field equations are derived from a variational Hilbert- Einstein's type principle.
The action for the $f(R,T)$ gravity is given by

$$S = \frac{1}{16\pi}\int f(R,T)\sqrt{-g}\ d^4x + \int L_m\sqrt{-g}\ d^4x, \tag{2}$$

where R, T, g and L_m are the Ricci scalar, the trace of the stress-energy tensor of matter T_{ij} , the determinant of the metric tensor g_{ij} and the matter Lagrangian density respectively.

The stress-energy tensor of matter is defined as

$$T_{ij} = -\frac{2}{\sqrt{-g}}\frac{\delta\left(\sqrt{-g}\ L_m\right)}{\delta g^{ij}}, \tag{3}$$

and its trace by $T = g^{ij}T_{ij}$.
Assuming that the Lagrangian density L_m of matter depends only on the components of the metric tensor g_{ij} and not on its derivatives which yields

$$T_{ij} = g_{ij} L_m - 2\frac{\partial L_m}{\partial g^{ij}} \, , \tag{4}$$

Varying the action S with respect to the metric tensor g_{ij}, the field equations in $f(R,T)$ theory of gravity are given by

$$f_R(R,T)R_{ij} - \frac{1}{2} f(R,T)g_{ij} - (\nabla_i \nabla_j - g_{ij} \Box) f_R(R,T) = 8\pi T_{ij} - f_T(R,T)(T_{ij} + \Theta_{ij}), \tag{5}$$

where $\Theta_{ij} = g^{ij}\left(\frac{\delta T_{ij}}{\delta g^{ij}}\right)$,which follows from the equation $g^{ij}\left(\frac{\delta T_{ij}}{\delta g^{ij}}\right) = T_{ij} + \Theta_{ij}$ and $\Box \equiv \nabla^i \nabla_i$ is the De Alembert's operator, f_R and f_T are the ordinary derivatives with respect to R and T respectively.

Contraction of equation (5) gives

$$f_R(R,T)R + 3\Box f_R(R,T) - 2f(R,T) = 8\pi T - f_T(R,T)(T + \Theta), \tag{6}$$

where $\Theta = g^{ij}\Theta_{ij} = \Theta_i^i$.

This is an important relation between Ricci scalar R and the trace T of energy momentum tensor.

Assume that the source is regarded as a perfect fluid, the stress-energy tensor of the matter Lagrangian is derived as

$$T_{ij} = (\rho + p)u_i u_j - pg_{ij}, \tag{7}$$

satisfying the equation of state

$$p = \varepsilon\rho, \; 0 \le \varepsilon \le 1, \tag{8}$$

The problem of perfect fluid described by an energy density ρ, pressure p and four velocity $u^i = (0,0,0,1)$ are not an easy task to deal and there is no any unique definition of matter Lagrangian. Thus we can assume $L_m = -p$, which gives

$$\Theta_{ij} = -2T_{ij} - p\, g_{ij}, \tag{9}$$

Using equations (9) , the field equations (5) can be written as

$$f_R(R,T)R_{ij} - \frac{1}{2} f(R,T)g_{ij} - (\nabla_i \nabla_j - g_{ij} \Box) f_R(R,T) = 8\pi T_{ij} + f_T(R,T)(T_{ij} + pg_{ij}), \tag{10}$$

It is important to note that the field equations in $f(R,T)$ gravity depend on the physical nature of the matter field through the tensor g_{ij}. Hence we can obtain different theoretical models for each choice of $f(R,T)$. However, Harko *et. al*. **[24]** gives three classes of models out of which we used $f(R,T) = R + 2f(T)$.

The gravitational field equations for the metric (1)becomes

$$R_{ij} - \frac{1}{2}Rg_{ij} = 8\pi T_{ij} + 2f'(T)T_{ij} + [f(T) + 2p\, f'(T)]g_{ij}, \tag{11}$$

where overhead prime denotes the derivative w.r.to. *T.*

Field Equations and Some Important Physical Properties

To solve the field equations we choose $f(T) = \mu T$, where μ is constant, so the fields equations becomes

$$\frac{\ddot{B}}{B} + \frac{\ddot{C}}{C} + \frac{\dot{B}\dot{C}}{BC} = (8\pi + 3\mu)p - \mu\rho, \tag{12}$$

$$\frac{\ddot{A}}{A} + \frac{\ddot{C}}{C} + \frac{\dot{A}\dot{C}}{AC} = (8\pi + 3\mu)p - \mu\rho, \tag{13}$$

$$\frac{\ddot{A}}{A}+\frac{\ddot{B}}{B}+\frac{\dot{A}\dot{B}}{AB}-\frac{\alpha^2}{A^2}=(8\pi+3\mu)p-\mu\rho, \tag{14}$$

$$\frac{\dot{A}\dot{B}}{AB}+\frac{\dot{B}\dot{C}}{BC}+\frac{\dot{A}\dot{C}}{AC}-\frac{\alpha^2}{A^2}=\mu p-(8\pi+3\mu)\rho, \tag{15}$$

$$\alpha\left[\frac{\dot{A}}{A}-\frac{\dot{B}}{B}\right]=0, \tag{16}$$

where overhead dot represents the derivative with respect to time t.
Integrating equation (16), we obtain

$$A=cB, \tag{17}$$

where c is a constant of integration .
For sake of simplicity, we take $c=1$, so that we have

$$A=B, \tag{18}$$

Using equation (18), the above field equations (12)- (15) can be written as

$$\frac{\ddot{A}}{A}+\frac{\ddot{C}}{C}+\frac{\dot{A}\dot{C}}{AC}=(8\pi+3\mu)p-\mu\rho, \tag{19}$$

$$2\frac{\ddot{A}}{A}+\left(\frac{\dot{A}}{A}\right)^2-\frac{\alpha^2}{A^2}=(8\pi+3\mu)p-\mu\rho, \tag{20}$$

$$\left(\frac{\dot{A}}{A}\right)^2+2\frac{\dot{A}\dot{C}}{AC}-\frac{\alpha^2}{A^2}=\mu p-(8\pi+3\mu)\rho, \tag{21}$$

The system of these three equations are highly nonlinear differential equations with four unknowns $A, C, \rho, p.$ To obtain exact solution of these field equations, we need one extra assumption among these unknowns.

We define the following parameters to be used in solving Einstein's field equations for the metric (1)
The spatial volume and the average scale factor for the metric (1) are given by

$$V=ABC, \tag{22}$$

$$a=V^{\frac{1}{3}}=(ABC)^{\frac{1}{3}}, \tag{23}$$

The average Hubble's parameter read as

$$H=\frac{\dot{V}}{3V}=\frac{\dot{a}}{a}=\frac{1}{3}\left[\frac{\dot{A}}{A}+\frac{\dot{B}}{B}+\frac{\dot{C}}{C}\right], \tag{24}$$

where $H_x=\frac{\dot{A}}{A}, H_y=\frac{\dot{B}}{B}, H_z=\frac{\dot{C}}{C}$ are the directional Hubble parameters along x, y and z axes respectively.
The cosmological inflation or the accelerated expansion of the universe is characterized by deceleration parameter q, so the important observational quantity q is defined as

$$q=-\frac{a\ddot{a}}{\dot{a}^2}=2-3\frac{V\ddot{V}}{\dot{V}^2}, \tag{25}$$

The sign q represents whether the model inflates or not. The positive value of deceleration parameter suggests a decelerating model while the negative value indicates inflation. If $q=0,$ then the universe expands at constant rate. Also, recent observations of SN Ia, reveal that the present universe is expanding and the value of q lies somewhere in the range $-1<q<0.$

Usual definition of the dynamical scalars such as the expansion scalar (θ) and shear scalar (σ^2) are considered to be

$$\theta = u^i_{;i} = \frac{\dot{A}}{A}+\frac{\dot{B}}{B}+\frac{\dot{C}}{C}, \tag{26}$$

$$\sigma^2 = \frac{1}{2}\sigma_{ij}\sigma^{ij} = \frac{\theta^2}{3} - \left[\frac{\dot{A}\dot{B}}{AB}+\frac{\dot{B}\dot{C}}{BC}+\frac{\dot{A}\dot{C}}{AC}\right], \tag{27}$$

where $\sigma_{ij} = \frac{1}{2}(\nabla_j u_i + \nabla_i u_j) - \frac{1}{3}g_{ij}\theta$. (28)

To examine whether expansion of the universe is anisotropic or not ,we define the anisotropy parameter $\overline{A}$

$$\overline{A} = \frac{1}{3}\sum_{i=1}^{3}\left(\frac{H_i - H}{H}\right)^2 = 6\left(\frac{\sigma}{\theta}\right)^2, \tag{29}$$

If $\overline{A}=0,$ then the universe expands isotropically. Further, any anisotropic model of the universe with diagonal energy-momentum tensor approaches to isotropy if $\overline{A}\to 0, V\to\infty$ and $\rho\to 0$ as $t\to+\infty.$

It is to note that, to determine the value of metric functions, the value of average scale factor $a(t)$ must be known. For constructing cosmological models, the deceleration parameter and Hubble parameter play a vital role in describing the behavior of universe. In literature it is commonly used a variation law of Hubble's parameter [33-41] that produces a constant value of deceleration parameter which subsequently leads to power law and exponential form of average scale factor $a(t).$ The recent observations show that the universe was decelerating in past and is accelerating at present time. Hence generally, the value of deceleration parameter is excepted to be not only a constant but also time dependent form. Many authors have proposed a time dependent forms of deceleration parameter and obtained the several forms of average scale factor of the model. Abdussattar and Prajapati [42], Akarsu and Dereli [43] proposed a time dependent deceleration parameter and obtained the accelerating cosmological solutions by considering the Roberson-Walker space-time filled with perfect fluid in General Relativity. However, some authors (Pradhan *et al.* [44], Anil Kumar Yadav [45], Saha *et al.*[46] etc.) first choose the average scale factor and then derive the time dependent deceleration parameter. Here we consider the special form of deceleration parameter for FRW space time proposed by Singh and Debnath [47] as

$$q = \frac{m}{1+a^m} - 1, \tag{30}$$

where $m>0$ is a parameter. Obviously, the several values of m will produce a several models.

Substituting equation (30) in (25) and integrated to give the time dependent form of average scale factor a as

$$a = \left(e^{kmt}-1\right)^{\frac{1}{m}}, \tag{31}$$

where k is a constant of integration.

Solution of Field Equations

To derive the cosmological models, we assume that $C=V^b$, where b is any constant.

Using equations (18), (23), (31), the scalar functions become

$$A = \left(e^{kmt}-1\right)^{\frac{3(1-b)}{2m}}, \tag{32}$$

$$B = \left(e^{kmt}-1\right)^{\frac{3(1-b)}{2m}}, \tag{33}$$

$$C=\left(e^{kmt}-1\right)^{\frac{3b}{m}}, \tag{34}$$

Hence the geometry of the universe (1) is reduced to

$$ds^2=dt^2-\left(e^{kmt}-1\right)^{\frac{3(1-b)}{m}}dx^2-\left(e^{kmt}-1\right)^{\frac{3(1-b)}{m}}e^{-2\alpha x}dy^2-\left(e^{kmt}-1\right)^{\frac{6b}{m}}dz^2. \tag{35}$$

The spatial volume is given by

$$V=\left(e^{kmt}-1\right)^{\frac{3}{m}}, \tag{36}$$

The directional Hubble parameters and average Hubble parameter turn out to be

$$H_x=\frac{3(1-b)ke^{kmt'}}{2(e^{kmt}-1)}, \tag{37}$$

$$H_y=\frac{3(1-b)ke^{kmt'}}{2(e^{kmt}-1)}, \tag{38}$$

$$H_z=\frac{3bke^{kmt'}}{e^{kmt}-1}, \tag{39}$$

$$H=\frac{ke^{kmt'}}{e^{kmt}-1}, \tag{40}$$

The deceleration parameter q becomes

$$q=\frac{m}{e^{kmt}}-1, \tag{41}$$

The value of expansion scalar θ and shear scalar σ^2 are given by

$$\theta=\frac{3ke^{kmt'}}{e^{kmt}-1}, \tag{42}$$

$$\sigma^2=3\frac{(9b^2-6b+1)k^2e^{2kmt'}}{(e^{kmt}-1)^2}, \tag{43}$$

The anisotropy parameter $\overline{A}$ is found to be

$$\overline{A}=\frac{9b^2-6b+1}{2}, \tag{44}$$

The value of energy density and pressure become

$$\rho=\frac{1}{4(\mu+2\pi)(\mu+4\pi)}\left\{\frac{(\mu+4\pi)\alpha^2}{(e^{kmt}-1)^{\frac{3(1-b)}{m}}}-\frac{3(1-b)k^2e^{kmt}}{2(e^{kmt}-1)^2}\left[3e^{kmt}(2\pi+3\mu b+6\pi b)+\mu m\right]\right\}, \tag{45}$$

$$p=\frac{\varepsilon}{4(\mu+2\pi)(\mu+4\pi)}\left\{\frac{(\mu+4\pi)\alpha^2}{(e^{kmt}-1)^{\frac{3(1-b)}{m}}}-\frac{3(1-b)k^2e^{kmt}}{2(e^{kmt}-1)^2}\left[3e^{kmt}(2\pi+3\mu b+6\pi b)+\mu m\right]\right\}, \tag{46}$$

Now we consider $f(T) = \mu T^2$, so equation (11) can be written as

$$R_{ij} - \frac{1}{2} R g_{ij} = (8\pi + 4\lambda T) T_{ij} + \lambda T (T + 4p) g_{ij}, \tag{47}$$

So the fields equations become

$$\frac{\ddot{B}}{B} + \frac{\ddot{C}}{C} + \frac{\dot{B}\dot{C}}{BC} = 8\pi p - 9\mu\rho^2 + 6\mu\rho p - \mu p^2,$$
(48)

$$\frac{\ddot{A}}{A} + \frac{\ddot{C}}{C} + \frac{\dot{A}\dot{C}}{AC} - \frac{\alpha^2}{A^2} = 8\pi p - 9\mu\rho^2 + 6\mu\rho p - \mu p^2, \tag{49}$$

$$\frac{\ddot{A}}{A} + \frac{\ddot{B}}{B} + \frac{\dot{A}\dot{B}}{AB} - \frac{1}{A^2} = 8\pi p - 9\mu\rho^2 + 6\mu\rho p - \mu p^2, \tag{50}$$

$$\frac{\dot{A}\dot{B}}{AB} + \frac{\dot{B}\dot{C}}{BC} + \frac{\dot{A}\dot{C}}{AC} - \frac{\alpha^2}{A^2} = 8\pi\rho + 5\mu\rho^2 - 14\mu\rho p - 3\mu p^2, \tag{51}$$

$$\alpha\left[\frac{\dot{A}}{A} - \frac{\dot{B}}{B}\right] = 0, \tag{52}$$

The above equations produce the same solution as that of given in equation (35).

By solving above equations, the energy density is given by

$$\rho^2 - \frac{8\pi}{\mu(3\omega + 14\omega - 5)}\rho + \frac{9(1-b)k^2(1+3b)e^{2kmt}}{4\mu(3\omega^2 + 14\omega - 5)(e^{kmt} - 1)^2} = 0. \tag{53}$$

This quadratic equation in ρ is due to the non linear form of $f(T)$.

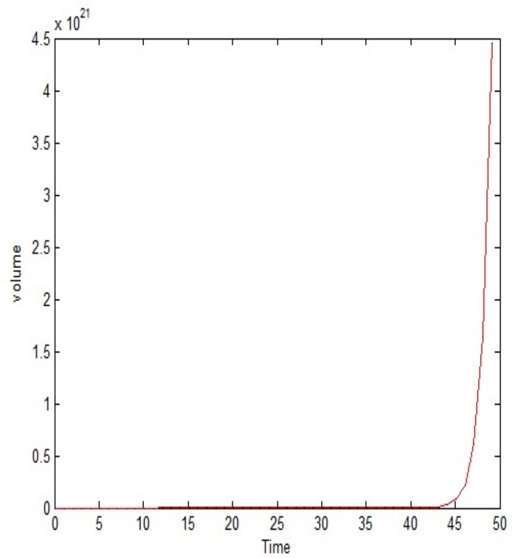

Fig 1 Volume vs Time

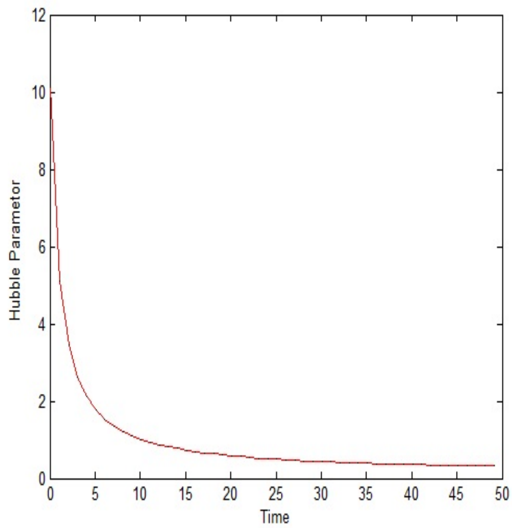

Fig 2 Hubble Parameter vs Time

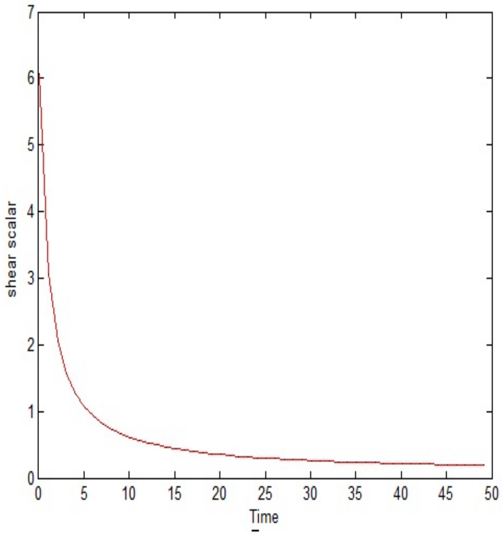

Fig 3 Shear Scalar vs Time

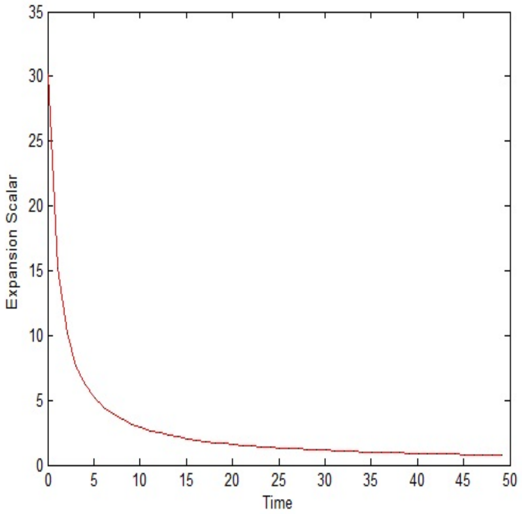

Fig 4 Expansion Scalar vs Time

CONCLUSION

In this paper, we have presented the new exact solution of Einstein's field equations for spatially homogeneous & anisotropic Bianchi-III cosmological model filled with perfect fluid in $f(R,T)$ theory of gravity. For this purpose we use $f(R,T) = R + \mu T$. we have evaluated some physical parameters for this solution such as $\theta, \sigma^2, \overline{A}$.

The model has initial singularity because the metric coefficients A, B and C vanish at initial moment. We observe that the volume of the universe is zero at $t = 0$ and increases exponentially with the cosmic time t as shown in the fig.(1) whereas the mean Hubble parameter H and shear scalar σ^2 are constant throughout the evolution as shown in fig. (2) and (3) which indicates the uniform exponential expansion of universe. Moreover $\frac{\sigma}{\theta}$ is constant, therefore the model do not approaches isotropy at any time. It is interesting to note that for the value of $b = \frac{1}{3}$, the anisotropic parameter $\overline{A}$ vanishes, therefore the space time anisotropy disappear & the models of our universe approaches isotropy for $b = \frac{1}{3}$

At $t \to \infty, q = -1$, i.e. this model accelerates. The physical parameters $H, \theta, \sigma^2, \rho, p$ diverge at the initial epoch & are constant for large value of t.

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