IRJSE *Int. Res. J. of Science & Engineering,* 2020; Special Issue A7: 181-188 SJIF Impact Factor 6.68
ISSN: 2322-0015
RESEARCH ARTICLE OPEN ACCESS

Bianchi Type-V Cosmological Model in Presence of Quadratic Equation of State in $f(R)$ Gravity

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Manuscript Details
Available online on http://www.irjse.in
ISSN: 2322-0015

Cite this article as:
Ladke LS, Tripade VP, Mishra RD, Gomkar SR. Bianchi Type-V Cosmological Model in Presence of Quadratic Equation of State in $f(R)$ Gravity., *Int. Res. Journal of Science & Engineering,* February 2020, Special Issue A7 : 181-188.

ABSTRACT

In this paper, we have studied Bianchi type-V cosmological model in presence of quadratic equation of state in $f(R)$ theory of gravity. Using assumption of constant Deceleration parameter and Hubble parameter proposed by Berman, we get two models. The behaviors of both the models have been discussed by studying some physical properties.

Keywords: Bianchi type-V metric, quadratic equation of state, $f(R)$ gravity, constant Deceleration parameter.

INTRODUCTION

Einstein general theory of relativity is sufficient to explain most of the gravitational phenomenon but it does not seem to resolve some of the problems in cosmology such as the accelerated expansion of the universe, energy localization problem. The experimental and theoretical data suggest that the universe is in accelerated phase. All the observations from the different sources such as supernova type-Ia experiments performs by different authors[1-4], large scale structure[5], cosmic microwave background fluctuations[6-8], X-ray experiments[9] suggest that the universe is expanding. Different models have been proposed for dark energy and dark matter. Dark matter has the same properties as ordinary matter but cannot be detected in laboratory.

To explain the accelerated expansion of the universe several theories of gravitation has been proposed as alternative to Einstein theory such as Brans and Dicke (1961), Nordtvedt (1970), Ross (1972), Dunn (1974), and saez Ballester theory (1986). The scalar field together with the metric tensor fields then forms scaler tensor field representing the gravitational fields.

Also to resolve the anomaly created due to the accelerated expansion of the universe, number of modified theories of gravitation such as f(R) theory, f(R,T) theory, f(T) theory etc have been proposed by different authors.

Among the modified theories of gravity it is proved that f(R) theory of gravity provides very natural unification of the early time inflation and late time acceleration. f(R) theory of gravity is considered as the most suitable theory. It has been observed that the natural gravitational alternative to dark energy is provided by this modified theory of gravity. Nojiri and Odintsov [10] proved that f(R) theory is the desirable candidate to overcome the issue of dark energy problems as well as singularity in general theory of relativity. In the context of non-singular oscillating cosmologies, Buchdhal [11] studied the action rigorously. Many researchers [12-16] have investigated f(R) gravity in different context the in homogeneity and anisotropy of the universe play an important role in modern cosmology. Bianchi type models are simplest models with anisotropic background, which is the generalization of FRW space-time.

M Sharif & H. Rizwana Kausar [17] discussed non-vacuum solutions of Bianchi type VIo universe in f(R) gravity considering isotropic perfect fluid. K.S. Adhav [18] studied LRS Bianchi type-I universe with anisotropic dark energy in lyra geometry. Kumar and Singh [19] discussed Bianchi type-I space-time in general relativity in the presence of perfect fluid. Aktas et al [20] have studied anisotropic model in f(R) theory of gravity. Reddy et al [21] studied vacuum solutions of Bianchi type I & V models in f(R) theory of gravity with a special form of decelerating parameter. M. Sharif and et. al. [22] explains anisotropic Bianchi type-III model in f(R) theory of gravity. M. Sharif and M. Farasat Shamir [23, 24] exhibit vacuum as well as non vacuum solutions. Solutions of Bianchi types-I and V space times in f(R) theory of gravity. K.S. Adhav [25] obtained Bianchi types-III string cosmological model in f(R) theory of gravity. M. Farasat Shamir [26] obtained exact solutions of Bianchi type I and V models in f(R, T) gravity with the assumption of constant deceleration parameter and variation law of Hubble parameter. Bianchi type-IX viscous stringing cosmologies model in f(R, T) gravity with special form of deceleration parameter is studied by H.R. Ghate et. al. [27]. The strong dissipation due to the neutrino viscosity may considerably reduce the anisotropy of the black body radiation studied by Misner [28, 29]. Coley [30] have studied Bianchi type-V viscous fluid cosmological models for a barometric fluid distribution. Singh and Baghel [31] examined Bianchi type-V cosmological Models with bulk viscosity. Kumar and Singh [32] solved Bianchi type-I space-time in general relativity in the presence of perfect fluid.

In this paper, we studied Bianchi type-V cosmological model in presence of quadratic equation of state in f(R) gravity. Here we used the assumption of constant deceleration parameter and Hubble parameter proposed by Berman M.S. [33]. Physical properties of both the models have been discussed.

2. Metric and Field equations in $f(R)$ gravity

We consider Bianchi type-V Space- time is

$$ds^2 = dt^2 - A^2(t)\,dx^2 - B^2(t)\,e^{2bx}dy^2 - C^2(t)\,e^{2bx}dz^2 \tag{1}$$

Where A, B, C are function of cosmic time t and b is arbitrary constant only.
The corresponding Ricci scalar curvature (R) is given by

$$R = -2\left[\frac{\ddot{A}}{A} + \frac{\ddot{B}}{B} + \frac{\ddot{C}}{C} + \frac{\dot{A}\dot{B}}{AB} + \frac{\dot{B}\dot{C}}{BC} + \frac{\dot{A}\dot{C}}{AC} - \frac{3b^2}{A^2}\right] \tag{2}$$

We will extract the field equations for this section. For this reason, we utilize the metric approach of $f(R)$ theory of gravity. In this approach, the variation of the action is done with respect to the metric tensor only.
The action of $f(R)$ theory is expressed as

$$S = \int \sqrt{-g}\left(\frac{1}{2k} f(R) + L_m\right) d^4x \tag{3}$$

Where $f(R)$ is a general function of Ricci scalar (R), $k = 8\pi G$, g is determinant of the metric g_{ij} and L_m is the matter Lagrangian. In the standard Einstein–Hilbert action the replacement of R by $f(R)$ gives us this action. By varying this action with respect to metric tensor g_{ij} , these corresponding field equations can be derived,

$$F(R)R_{ij} - \frac{1}{2} f(R)g_{ij} - \nabla_i \nabla_j F(R) + g_{ij} \Box F(R) = \kappa T_{ij} \tag{4}$$

Where $F(R) = {df(R)}/{dR}$, $\Box \equiv \nabla^i \nabla_i$, (5)

∇_i is the covariant derivative, T_{ij} is the standard matter energy-momentum tensor derived from Lagrangian L_m .

Let us consider that the matter content is a perfect fluid such that the energy- momentum tensor as

$$T_{ij} = (p+\rho)u_i u_j - p g_{ij} \tag{6}$$

where u^i is the four-velocity vector of the fluid satisfying $u^i = (0,0,0,1)$ and $u^i u_j = 1$, p and ρ be the pressure and energy density of the fluid respectively satisfying quadratic equation of state

$$p = \varepsilon\rho^2 - \rho \tag{7}$$

Where ε is the constant and $\varepsilon \neq 0$

From Eqns (5), we get energy- momentum tensor for satisfying quadratic equation of state is given by

$$T_{ij} = \varepsilon\rho^2 u_i u_j - (\varepsilon\rho^2 - \rho) g_{ij} \tag{8}$$

Using co-moving coordinates, field equations (4) for metric (1) yield the following equations:

$$\left(\frac{\ddot{A}}{A} + \frac{\dot{A}\dot{B}}{AB} + \frac{\dot{A}\dot{C}}{AC} - \frac{2b^2}{A^2}\right)F + \frac{1}{2} f(R) - \left(\frac{\dot{B}}{B} + \frac{\dot{C}}{C}\right)\dot{F} - \ddot{F} = k(\varepsilon\rho^2 - \rho) \tag{9}$$

$$\left(\frac{\ddot{B}}{B} + \frac{\dot{A}\dot{B}}{AB} + \frac{\dot{B}\dot{C}}{BC} - \frac{2b^2}{A^2}\right)F + \frac{1}{2} f(R) - \left(\frac{\dot{A}}{A} + \frac{\dot{C}}{C}\right)\dot{F} - \ddot{F} = k(\varepsilon\rho^2 - \rho) \tag{10}$$

$$\left(\frac{\ddot{C}}{C} + \frac{\dot{C}\dot{B}}{CB} + \frac{\dot{A}\dot{C}}{AC} - \frac{2b^2}{A^2}\right)F + \frac{1}{2} f(R) - \left(\frac{\dot{B}}{B} + \frac{\dot{A}}{A}\right)\dot{F} - \ddot{F} = k(\varepsilon\rho^2 - \rho) \tag{11}$$

$$\left(\frac{\ddot{A}}{A} + \frac{\ddot{B}}{B} + \frac{\ddot{C}}{C}\right)F + \frac{1}{2} f(R) - \left(\frac{\dot{A}}{A} + \frac{\dot{B}}{B} + \frac{\dot{C}}{C}\right)\dot{F} = -\rho k \tag{12}$$

$$\left(\frac{\dot{B}}{B} - \frac{\dot{A}}{A}\right)F = 0 \tag{13}$$

3. Solutions of the field equations:

Integrating (13), we obtain

$$A = c_2 B \tag{14}$$

Where c_2 is an integration constant, which can be chosen as unity without loss of any generality, so that we get

$$A = B \tag{15}$$

Now, using (15), field equations (9)–(13) reduce to the following independent equations:

$$\left(\frac{\ddot{A}}{A} + \frac{\dot{A}^2}{A^2} + \frac{\dot{A}\dot{C}}{AC} - \frac{2b^2}{A^2}\right)F + \frac{1}{2} f(R) - \left(\frac{\dot{A}}{A} + \frac{\dot{C}}{C}\right)\dot{F} - \ddot{F} = k(\varepsilon\rho^2 - \rho) \tag{16}$$

$$\left(\frac{\ddot{C}}{C}+2\frac{\dot{A}\dot{C}}{AC}-\frac{2b^2}{A^2}\right)F+\frac{1}{2}f(R)-2\left(\frac{\dot{A}}{A}\right)\dot{F}-\ddot{F}=k(\varepsilon\rho^2-\rho) \tag{17}$$

$$\left(2\frac{\ddot{A}}{A}+\frac{\ddot{C}}{C}\right)F+\frac{1}{2}f(R)-\left(2\frac{\dot{A}}{A}+\frac{\dot{C}}{C}\right)\dot{F}=-\rho k \tag{18}$$

Spatial volume and average scale factor of the model

$$V = A^2C, \qquad a(t)=(A^2C)^{\frac{1}{3}} \tag{19}$$

Anisotropic parameter A_n is given by

$$A_n=\frac{1}{3}\sum_{i=1}^{3}\left(\frac{H_i-H}{H}\right)^2 \tag{20}$$

Where $H_1=H_2=\frac{\dot{A}}{A}$, $H_3=\frac{\dot{C}}{C}$ directional Hubble's parameter and mean Hubble's parameter is given by

$$H=\frac{1}{3}\left(2\frac{A}{A}+\frac{\dot{C}}{C}\right) \tag{21}$$

Expansion scalar and shear scalar are defined as

$$\theta=3H=\left(2\frac{A}{A}+\frac{\dot{C}}{C}\right) \tag{23}$$

$$\sigma^2=\frac{1}{3}\sigma^{ij}\sigma_{ij}=\frac{1}{3}\left(\frac{\dot{A}}{A}-\frac{\dot{C}}{C}\right)^2 \tag{23}$$

We define deceleration parameter is given by

$$q=\frac{d}{dt}\left(\frac{1}{H}\right)-1 \tag{24}$$

The σ^2 shear scalar is proportional to θ scalar expansion, which leads to a relation

$$A=C^n \tag{25}$$

Where n ≠ 0 is a constant and preserves the anisotropic character of the space-time. Uddin et al. have established a result in f(R) gravity as $F(t)\,\alpha\, a^m$

Thus using power-law relation between F *and* a,
we have

$$F(t)=F_0\,(a(t))^m \tag{26}$$

Where F_0 proportionality constant and m is an arbitrary constant.

The Hubble parameter H proposed by Berman defined as

$$H=\alpha\, a^{-\beta} \tag{27}$$

Where $\alpha>0$, $\beta\geq 0$ are constants and $a(t)$ is average scale factor. This relation gives a constant value of deceleration parameter. By solving (27), we obtain

$$a(t)=(\beta\alpha t+c_4)^{1/\beta} \qquad \text{For } \beta\neq 0 \tag{28}$$

$$a(t) = c_5 e^{\alpha t} \qquad \text{For } \beta = 0 \qquad (29)$$

These are two different values of average scale factor.

3.1 Model with $\beta \neq 0$

From (15), (19) (25), and (28), we get the metric coefficients for power law expansion model of the universe as

$$A = B = V^{-1/2(2n+1)}(\alpha\beta t + c_4)^{3/2\beta}, \qquad C = V^{-2n/(2n+1)}(\alpha\beta t + c_4)^{3/\beta}$$

(30)

From (26) and (28), the function F(R) becomes

$$F = F_0 a^m = F_0(\beta\alpha t + c_4)^{m/\beta} \qquad (31)$$

From (16)–(18), we get the pressure and energy density of the fluid is given by

$$\varepsilon\rho^2 = \frac{F_0(\beta\alpha t + c_4)^{(m-3)/\beta}}{k}\left[\alpha^2\left(\frac{18n(1-n) + 12\beta n^2 + 6mn + 3m - m(m-\beta)(2n+1)^2}{(2n+1)^2(\alpha\beta t + c_4)^{\frac{2\beta-3}{\beta}}}\right) - \frac{2b^2}{V^{-1/(2n+1)}}\right] \qquad (32)$$

$$\rho = \left[\frac{9(n - 2n^2 + 1) - 24n\beta(n+1) + 3\beta(10n^2 + 5n - 1) - 3m(2n^2 - n - 1)}{2k(2n+1)^2(\alpha\beta t + c_4)^{2-\frac{m}{\beta}}}\right]F_0\alpha^2 \qquad (33)$$

$$p = \left[\left(\frac{9(5n - 6n^2 + 1) + 3\beta(10n^2 + 3n - 1) + 3m(5n - 2n^2 + 3) - 2m(m-\beta)(2n+1)^2}{2k(2n+1)^2(\alpha\beta t + c_4)^{2-\frac{m}{\beta}}}\right)F_0\alpha^2 - \frac{2b^2}{kV^{\frac{-1}{(2n+1)}}}F_0(\beta\alpha t + c_4)^{(m-3)/\beta}\right] \qquad (34)$$

The scalar curvature R and $f(R)$ function are found as

$$f(R) = \left[\frac{9(n - 6n^2 - 1) - 3\beta(10n^2 + 5n + 1) + 9m(2n^2 + 3n + 1)}{(2n+1)^2(\alpha\beta t + c_4)^{2-\frac{m}{\beta}}}\right]\alpha^2 F_0 \qquad (35)$$

$$R = -2\alpha^2\left[\frac{27n^2 - 12\beta n(n+1) + 9(2n+1) - 3\beta}{(2n+1)^2(\alpha\beta t + c_4)^2}\right] + \frac{6b^2}{V^{\frac{-1}{(2n+1)}}}(\alpha\beta t + c_4)^{3/\beta} \qquad (36)$$

Now metric (1) can be written as

$$ds^2 = dt^2 - V^{-1/(2n+1)}(\alpha\beta t + c_4)^{3/\beta}dx^2 - V^{-1/(2n+1)}(\alpha\beta t + c_4)^{3/\beta}e^{2bx}dy^2 - V^{-4n/(2n+1)}(\alpha\beta t + c_4)^{6/\beta}e^{2bx}dz^2$$

$$ds^2 = dt^2 - V^{-1/(2n+1)}(\alpha\beta t + c_4)^{3/\beta}(dx^2 + e^{2bx}dy^2) - V^{-4n/(2n+1)}(\alpha\beta t + c_4)^{6/\beta}e^{2bx}dz^2$$

(37)

Thus, metric (37) together with (32)–(36) constitutes a Bianchi type-V cosmological model with Quadratic equation of state in $f(R)$ theory of gravity.

Properties of the model

Spatial volume of the model

$$V = (\beta \alpha t + c_4)^{3/\beta} \tag{38}$$

Directional Hubble's parameters are

$$H_1 = H_2 = \frac{3n\alpha}{(2n+1)(\alpha\beta t + c_4)} \quad , \quad H_3 = \frac{3\alpha}{(2n+1)(\alpha\beta t + c_4)} \tag{39}$$

Hubble's parameter is

$$H = \frac{\alpha}{(\alpha\beta t + c_4)} \tag{40}$$

Expansion scalar and shear scalar are given by

$$\theta = \frac{3\alpha}{(\alpha\beta t + c_4)} \quad \sigma^2 = \frac{3(n-1)^2 \alpha}{(2n+1)^2 (\alpha\beta t + c_4)^2} \tag{41}$$

Anisotropic parameter A_n and deceleration parameter q are given by

$$A_n = \frac{2(n-1)^2}{(2n+1)^2} \tag{42}$$

$$q = \beta - 1 \tag{43}$$

3.2. Model with $(\beta = 0)$

In this case, we get the average scale factor as

$$a(t) = c_5 e^{\alpha t} \tag{44}$$

From (15), (19), (25,) (26), and (29) metric coefficient for exponential expansion model of the universe, the scale factors and the function F(R) as

$$A = B = V^{-1/2(2n+1)} e^{\frac{3\alpha t}{2}} \quad , \quad C = V^{-2n/(2n+1)} e^{3\alpha t} \tag{45}$$

$$F = F_0 c_6 e^{m\alpha t} \tag{46}$$

From (16)–(18), we get the pressure and energy density of the fluid is given by

$$\varepsilon\rho^2 = \frac{F_0 c_6 e^{(m-3)\alpha t}}{k} \left[\alpha^2 \left(\frac{18n(1-n) + 6mn + 3m - m^2 (2n+1)^2}{(2n+1)^2 e^{-3\alpha t}} \right) - \frac{2b^2}{c_5 V^{-1/(2n+1)}} \right] \tag{47}$$

$$\rho = \left[\frac{9(n - 2n^2 + 1) - 3m(2n^2 - n - 1)}{2k(2n+1)^2} \right] F_0 c_6 \alpha^2 e^{m\alpha t} \tag{48}$$

$$p = \left[\begin{array}{l} \left(\dfrac{9(5n - 6n^2 + 1) + 3m(5n - 2n^2 + 3) - 2m^2 (2n+1)^2}{2k(2n+1)^2 e^{-m\alpha t}} \right) F_0 c_6 \alpha^2 \\ - \dfrac{2b^2}{k c_5 V^{\frac{-1}{(2n+1)}}} F_0 c_6 e^{\alpha t(m-3)} \end{array} \right] \tag{49}$$

The scalar curvature R and $f(R)$ function, we obtained

$$f(R)=\left[\frac{9(n-6n^2-1)+9m(2n^2+3n+1)}{(2n+1)^2}\right]\alpha^2 F_0 c_6 e^{m\alpha t} \quad (50)$$

$$R=-2\alpha^2\left[\frac{9(3n^2+2n+1)}{(2n+1)^2}\right]+\frac{6b^2}{c_5 V^{\frac{-1}{(2n+1)}}}e^{-3\alpha t} \quad (51)$$

Now metric (1) can be gives as

$$ds^2=dt^2-V^{-1/(2n+1)}c_5 e^{3\alpha t}(dx^2+e^{2bx}dy^2)-V^{-4n/(2n+1)}c_5^2 e^{6\alpha t}e^{2bx}dz^2 \quad (52)$$

Properties of the model.

Spatial volume of the model

$$V=c_5 e^{3\alpha t} \quad (53)$$

Directional Hubble's parameters, Hubble's parameter and expansion scalar are given by

$$H_1=H_2=\frac{3n\alpha}{(2n+1)}\ ,\ H_3=\frac{3\alpha}{(2n+1)} \quad (54)$$

$$H=\alpha \quad (55)$$

$$\theta=3\alpha \quad (56)$$

Shear scalar, mean anisotropic parameter and deceleration parameter are given by

$$\sigma^2=\frac{3(n-1)^2\alpha}{(2n+1)^2} \quad (57)$$

$$A_n=\frac{2(n-1)^2}{(2n+1)^2} \quad (58)$$

$$q=-1 \quad (59)$$

SUMMARY AND CONCLUSION

In this paper, we have studied Bianchi type-V model in presence of quadratic equation of state in f(R) theory of gravity. We assume here the constant deceleration parameter and Hubble parameter proposed by Berman. Also we have used power law relation between F and a and shear scalar b is proportional to scalar expansion θ which leads to a relation $A=c^n$. This gives the values of scale factor which corresponds to two models of the universe.

For the first model, average scale factor is $a=(\beta\alpha t+c_n)^{1/\beta}$. the mean generalized Hubble parameter, expansion scalar θ, Shear Scalar σ^2 are infinite at $t=0$ where as volume scale factor and anisotropic parameter are constant. The deceleration parameter is constant. The positive sign of q correspond to deceleration model, negative of q indicates inflation and for $q=0$, the universe expands at constant rate. These observations suggest that universe is expanding.

For the second model average scale factor is $a=c_n\exp(\alpha t)$. volume of the universe and metric coefficient increase exponentially with cosmic time t. Mean Hubble parameter, expansion scalar θ, shear scalar and anisotropic parameter are constant through out the evolution. The value of deceleration parameter is -1 for this model which indicates that the universe is in accelerating phase

Conflicts of interest: The authors stated that no conflicts of interest.

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