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BIANCHI TYPE-V COSMOLOGICAL MODEL IN LYRA MANIFOLD

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Bianchi type-V space-time is considered in the presence of a perfect fluid source in the framework of Lyra manifold with pressure equal to energy density ($p = \rho$). Some physical and geometrical properties of the model are discussed.

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1. *Introduction*

Weyl [1] proposed a modification of Riemannian manifold in order to unify gravitation and electromagnetism, but this theory was not accepted due to the non-integrability of length transfer. Later Lyra [2] proposed an additional modification of Riemannian geometry. In this theory, he introduced a gauge function, which removes the non-integrability condition of a vector under parallel transport. Subsequently, Sen [3] and Sen and Dunn [4] proposed a new scalar-tensor theory of gravitation based on Lyra geometry. Halford [5] found that energy-conservation law does not hold in the cosmological theory based on Lyra geometry. Halford [6] showed that the scalar-tensor theory of gravitation in Lyra manifold predicts the same effects within observational limits, as in the Einstein theory. Mohanty and Panigrahi [7] discussed the relation between Einstein's theory of gravitation and scalar-tensor theory of Sen and Dunn. Various authors (Bhamra [8], Karade and Borkar [9], Beesham [10, 11], Reddy and Venkateswaralu [12], Singh and Singh [13, 14], Singh and Desikan [15], Rahaman and Bera [16], Rahaman et al. [17], Reddy [18]) constructed different four-dimensional cosmological models in Lyra manifold. Rahaman et al. [17, 19] Singh et al. [20] and Mohanty et al. [21] constructed various five-dimensional cosmological models in Lyra manifold.

In this paper we obtained exact solutions of vacuum field equations in Lyra geometry. Further the exact solutions of the field equations are obtained when the source of gravitation is a stiff fluid.

In Section 2, we obtain the field equations based on Lyra manifold. In Section 3, we derive the explicit exact solutions of the field equations for vacuum model and stiff fluid model. In Section 4, some physical and geometrical features of the models are discussed.

2. *Metric and field equations*

The Einstein's field equations based on Lyra's manifold as proposed by Sen [3] and Sen and Dunn [4] in normal gauge may be written as

$$R_{ik} - \frac{1}{2} g_{ik} R + \frac{3}{2} \phi_i \phi_k - \frac{3}{4} g_{ik} \phi_m \phi^m = -\chi T_{ik} \,, \tag{1}$$

where ϕ_i is the displacement vector and other symbols have their usual meanings in the Riemannian geometry. Here we consider the four-dimensional Bianchi type-V metric in the form

$$\mathrm{d}s^2 = \mathrm{d}t^2 - a_1^2 \mathrm{d}x^2 - a_2^2 \mathrm{e}^{-2mx} \mathrm{d}y^2 - a_3^2 \mathrm{e}^{-2mx} \mathrm{d}z^2 \,. \tag{2}$$

The energy-momentum tensor for perfect fluid distribution is taken as

$$T_{ik} = (p + \rho) u_i u_k - p g_{ik} \,, \tag{3}$$

together with the co-moving co-ordinates

$$g^{ik} u_i u_k = 1 \,, \tag{4}$$

where p and ρ are the isotropic pressure and the energy density of the cosmic fluid distribution, respectively, and u_i is the four-velocity vector of the fluid which has components $(1, 0, 0, 0)$.

The displacement vector ϕ_h is defined as

$$\phi_h = (\beta(t), 0, 0, 0) \,. \tag{5}$$

The field Eqs. (1) together with Eqs. (3), (4) and (5) for the metric (2) yield the following explicit equations

$$\frac{\ddot{a}_2}{a_2} + \frac{\ddot{a}_3}{a_3} + \frac{\dot{a}_2 \dot{a}_3}{a_2 a_3} - \frac{m^2}{a_1^2} + \frac{3}{4} \beta^2 = -\chi p \,, \tag{6}$$

$$\frac{\ddot{a}_1}{a_1} + \frac{\ddot{a}_3}{a_3} + \frac{\dot{a}_1\dot{a}_3}{a_1a_3} - \frac{m^2}{a_1^2} + \frac{3}{4}\beta^2 = -\chi p\,, \tag{7}$$

$$\frac{\ddot{a}_1}{a_1} + \frac{\ddot{a}_2}{a_2} + \frac{\dot{a}_1\dot{a}_2}{a_1a_2} - \frac{m^2}{a_1^2} + \frac{3}{4}\beta^2 = -\chi p\,, \tag{8}$$

$$\frac{\dot{a}_1\dot{a}_2}{a_1a_2} + \frac{\dot{a}_2\dot{a}_3}{a_2a_3} + \frac{\dot{a}_3\dot{a}_1}{a_3a_1} - \frac{3m^2}{a_1^2} - \frac{3}{4}\beta^2 = \chi\rho\,, \tag{9}$$

and

$$\frac{2\dot{a}_1}{a_1} = \frac{\dot{a}_2}{a_2} + \frac{\dot{a}_3}{a_3}\,. \tag{10}$$

3. Solution of the field equations

3.1. Vacuum model

In the vacuum model ($p = 0$ and $\rho = 0$), the field Eqs. (6) to (10) reduce to

$$\frac{\ddot{a}_2}{a_2} + \frac{\ddot{a}_3}{a_3} + \frac{\dot{a}_2\dot{a}_3}{a_2a_3} - \frac{m^2}{a_1^2} + \frac{3}{4}\beta^2 = 0\,, \tag{11}$$

$$\frac{\ddot{a}_1}{a_1} + \frac{\ddot{a}_3}{a_3} + \frac{\dot{a}_1\dot{a}_3}{a_1a_3} - \frac{m^2}{a_1^2} + \frac{3}{4}\beta^2 = 0\,, \tag{12}$$

$$\frac{\ddot{a}_1}{a_1} + \frac{\ddot{a}_2}{a_2} + \frac{\dot{a}_1\dot{a}_2}{a_1a_2} - \frac{m^2}{a_1^2} + \frac{3}{4}\beta^2 = 0\,, \tag{13}$$

$$\frac{\dot{a}_1\dot{a}_2}{a_1a_2} + \frac{\dot{a}_2\dot{a}_3}{a_2a_3} + \frac{\dot{a}_3\dot{a}_1}{a_3a_1} - \frac{3m^2}{a_1^2} - \frac{3}{4}\beta^2 = 0\,, \tag{14}$$

and

$$a_2a_3 = a_1^2\,. \tag{15}$$

Subtracting Eq. (11) from Eq. (12), we get

$$\frac{\ddot{a}_1}{a_1} - \frac{\ddot{a}_2}{a_2} + \frac{\dot{a}_1\dot{a}_3}{a_1a_3} - \frac{\dot{a}_2\dot{a}_3}{a_2a_3} = 0\,. \tag{16}$$

Rearranging Eq. (16), we obtain

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\dot{a}_1}{a_1} - \frac{\dot{a}_2}{a_2}\right) + \left(\frac{\dot{a}_1}{a_1} - \frac{\dot{a}_2}{a_2}\right)\left(\frac{\dot{a}_1}{a_1} + \frac{\dot{a}_2}{a_2} + \frac{\dot{a}_3}{a_3}\right) = 0\,. \tag{17}$$

Following Saha [22], we consider here v as a function of t defined by

$$v = a_1 a_2 a_3 \,. \tag{18}$$

From Eq. (18), we get

$$\frac{\dot{v}}{v} = \frac{\dot{a}_1}{a_1} + \frac{\dot{a}_2}{a_2} + \frac{\dot{a}_3}{a_3} \,. \tag{19}$$

Substituting the value of $\dot{v}/v$ in Eq. (17), we find

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\dot{a}_1}{a_1} - \frac{\dot{a}_2}{a_2}\right) + \left(\frac{\dot{a}_1}{a_1} - \frac{\dot{a}_2}{a_2}\right)\frac{\dot{v}}{v} = 0 \,. \tag{20}$$

The above Eq. (20) is of the form

$$\frac{\mathrm{d}y}{\mathrm{d}t} + p(t) y = Q(t) \,, \tag{21}$$

which is a linear differential equation of the first order. Now integrating Eq. (20), we obtain

$$\frac{a_1}{a_2} = d_1 \exp\left(x_1 \int \frac{\mathrm{d}t}{v}\right) \,, \tag{22}$$

where d_1 and x_1 are constants of integration.

Subtracting Eq. (11) from Eq. (13), we get

$$\frac{\ddot{a}_1}{a_1} - \frac{\ddot{a}_3}{a_3} + \frac{\dot{a}_1 \dot{a}_2}{a_1 a_2} - \frac{\dot{a}_2 \dot{a}_3}{a_2 a_3} = 0 \,. \tag{23}$$

Rearranging Eq. (23), we obtain

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\dot{a}_1}{a_1} - \frac{\dot{a}_3}{a_3}\right) + \left(\frac{\dot{a}_1}{a_1} - \frac{\dot{a}_3}{a_3}\right)\left(\frac{\dot{a}_1}{a_1} + \frac{\dot{a}_2}{a_2} + \frac{\dot{a}_3}{a_3}\right) = 0 \,. \tag{24}$$

Now using Eq. (19) in Eq. (24) we get

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\dot{a}_1}{a_1} - \frac{\dot{a}_3}{a_3}\right) + \left(\frac{\dot{a}_1}{a_1} - \frac{\dot{a}_3}{a_3}\right)\frac{\dot{v}}{v} = 0 \,. \tag{25}$$

Integrating Eq. (25) we obtain

$$\frac{a_1}{a_3} = d_2 \exp\left(x_2 \int \frac{\mathrm{d}t}{v}\right) \,, \tag{26}$$

where d_2 and x_2 are constants of integration.

Subtracting Eq. (12) from Eq. (13), we get

$$\frac{\ddot{a}_2}{a_2} - \frac{\ddot{a}_3}{a_3} + \frac{\dot{a}_1\dot{a}_2}{a_1a_2} - \frac{\dot{a}_1\dot{a}_3}{a_1a_3} = 0\,. \tag{27}$$

Rearranging Eq. (27) we find

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\dot{a}_2}{a_2} - \frac{\dot{a}_3}{a_3}\right) + \left(\frac{\dot{a}_2}{a_2} - \frac{\dot{a}_3}{a_3}\right)\left(\frac{\dot{a}_1}{a_1} + \frac{\dot{a}_2}{a_2} + \frac{\dot{a}_3}{a_3}\right) = 0\,. \tag{28}$$

Using Eq. (19) in Eq. (28) we obtain

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\dot{a}_2}{a_2} - \frac{\dot{a}_3}{a_3}\right) + \left(\frac{\dot{a}_2}{a_2} - \frac{\dot{a}_3}{a_3}\right)\frac{\dot{v}}{v} = 0\,. \tag{29}$$

Integrating Eq. (29) we get

$$\frac{a_2}{a_3} = d_3 \exp\left(x_3 \int \frac{\mathrm{d}t}{v}\right), \tag{30}$$

where d_3 and x_3 are constants of integration.

From Eqs. (22), (26) and (30), we find the relation between the constants d_1, d_2, d_3 and x_1, x_2, x_3 as

$$d_1 d_3 = d_2, \qquad \text{and} \qquad x_1 + x_3 = x_2\,. \tag{31}$$

Equations (22), (26) and (30) with the help of Eqs. (15) and (18) reduce to

$$a_1(t) = D_1\, v^{1/3} \exp\left(X_1 \int \frac{\mathrm{d}t}{v(t)}\right), \tag{32}$$

$$a_2(t) = D_2\, v^{1/3} \exp\left(X_2 \int \frac{\mathrm{d}t}{v(t)}\right), \tag{33}$$

and

$$a_3(t) = D_3\, v^{1/3} \exp\left(X_3 \int \frac{\mathrm{d}t}{v(t)}\right), \tag{34}$$

where $D_i\,(i = 1, 2, 3)$ and $X_i\,(i = 1, 2, 3)$ satisfy the relations

$$D_1 D_2 D_3 = 1, \qquad \text{and} \qquad X_1 + X_2 + X_3 = 0\,.$$

Using Eqs. (32), (33) and (34) in Eq. (15) we get

$$\frac{D_2 D_3}{D_1} = \exp\left[(X_2 + X_3 - 2X_1)\int \frac{\mathrm{d}t}{v(t)}\right] = 1\,. \tag{35}$$

Since $X_1 + X_2 + X_3 = 0$, Eq. (35) yields

$$\frac{D_2 D_3}{D_1} = \exp\left[(-3X_1)\int \frac{\mathrm{d}t}{v(t)}\right] = 1\,.$$

Put $X_1 = 0$ in above equation, we get the relation $D_2 D_3 = D_1^2$, but from $D_1 D_2 D_3 = 1$, we obtain $D_1^3 = 1$.

Therefore, we can take

$$D_1 = 1, \quad X_1 = 0, \quad X_2 = -X_3 = X \quad \text{and} \quad D_2 = D_3^{-1} = D\,,$$

where D_1, D_2, D_3 and X_1, X_2, X_3 are constants of integration.

Finally, we write Eqs. (32), (33) and (34) as

$$a_1(t) = v^{1/3}\,, \tag{36}$$

$$a_2(t) = D v^{1/3} \exp\left(X \int \frac{\mathrm{d}t}{v(t)}\right)\,, \tag{37}$$

and

$$a_3(t) = D^{-1} v^{1/3} \exp\left(-X \int \frac{\mathrm{d}t}{v(t)}\right)\,, \tag{38}$$

where X and D are constants of integration.

Adding Eqs. (11), (12) and (13) with 3-times Eq. (14), we get

$$2\left(\frac{\ddot{a}_1}{a_1} + \frac{\ddot{a}_2}{a_2} + \frac{\ddot{a}_3}{a_3}\right) + 4\left(\frac{\dot{a}_1\dot{a}_2}{a_1 a_2} + \frac{\dot{a}_2\dot{a}_3}{a_2 a_3} + \frac{\dot{a}_3\dot{a}_1}{a_3 a_1}\right) - \frac{12m^2}{a_1^2} = 0\,, \tag{39}$$

i.e.

$$\left(\frac{\ddot{a}_1}{a_1} + \frac{\ddot{a}_2}{a_2} + \frac{\ddot{a}_3}{a_3}\right) + 2\left(\frac{\dot{a}_1\dot{a}_2}{a_1 a_2} + \frac{\dot{a}_2\dot{a}_3}{a_2 a_3} + \frac{\dot{a}_3\dot{a}_1}{a_3 a_1}\right) - \frac{6m^2}{a_1^2} = 0\,. \tag{40}$$

From Eq. (18) we get

$$\frac{\ddot{v}}{v} = \left(\frac{\ddot{a}_1}{a_1} + \frac{\ddot{a}_2}{a_2} + \frac{\ddot{a}_3}{a_3}\right) + 2\left(\frac{\dot{a}_1\dot{a}_2}{a_1 a_2} + \frac{\dot{a}_2\dot{a}_3}{a_2 a_3} + \frac{\dot{a}_3\dot{a}_1}{a_3 a_1}\right)\,. \tag{41}$$

Substituting Eq. (41) in Eq. (40) we find

$$\frac{\ddot{v}}{v} - \frac{6m^2}{a_1^2} = 0\,. \tag{42}$$

From Eqs. (15) and (18) we get

$$a_1 = v^{1/3}\,. \tag{43}$$

Using Eq. (43) in Eq. (42) we obtain

$$\ddot{v} = 6m^2 v^{1/3} \,. \tag{44}$$

Equation (44) can now be written as

$$\dot{v}\mathrm{d}\dot{v} = 6m^2 v^{1/3} \mathrm{d}v \,. \tag{45}$$

Integrating Eq. (45), we get

$$\dot{v}^2 = 9m^2 v^{4/3} + c_1 \,. \tag{46}$$

Taking square root of both sides of Eq. (46), we get

$$\dot{v} = \sqrt{9m^2 v^{4/3} + c_1} \,. \tag{47}$$

For simplicity, we take $c_1 = 0$. Now Eq. (47) reduces to

$$\dot{v} = \sqrt{9m^2 v^{4/3}} \,. \tag{48}$$

Integrating Eq. (48) we obtain

$$v = m^3 t^3 + t_0 \,, \tag{49}$$

where the integration constant t_0 can be taken to be zero, since it only gives shift in time.

Substituting the value $v = m^3 t^3$ in Eqs. (36), (37) and (38), we obtain

$$a_1(t) = mt \,, \tag{50}$$

$$a_2(t) = Dmt \exp\left(-\frac{X}{2m^3 t^2}\right) \,, \tag{51}$$

and

$$a_3(t) = D^{-1} mt \exp\left(\frac{X}{2m^3 t^2}\right) \,. \tag{52}$$

Using Eqs. (50), (51) and (52) in Eq. (14) we find

$$\beta^2 = -\frac{4}{3} \frac{X^2}{m^6} \, t^{-6} \,. \tag{53}$$

Equation (53) indicates that value of β^2 is negative which is acceptable. Halford [5] showed that β^2 can be considered as positive or negative for various realistic physical situations. At initial epoch $t = 0$, $\beta \to \infty$, and as $t \to \infty$, $\beta \to 0$. Thus the concept of Lyra geometry will not remain for a very long time.

In this case, the metric (2) takes the form

$$\mathrm{d}s^2 = \mathrm{d}t^2 - m^2t^2\mathrm{d}x^2 - D^2m^2t^2 \exp\left(-\frac{X}{m^3t^2} - 2mx\right)\mathrm{d}y^2$$

$$+D^{-2}m^2t^2 \exp\left(\frac{X}{m^3t^2} - 2mx\right)\mathrm{d}z^2\,, \tag{54}$$

3.2. *Stiff fluid model (Zel'dovich model)*

In this case $p = \rho$. Then the field Eqs. (6) to (10) reduce to

$$\frac{\ddot{a}_2}{a_2} + \frac{\ddot{a}_3}{a_3} + \frac{\dot{a}_2\dot{a}_3}{a_2a_3} - \frac{m^2}{a_1^2} + \frac{3}{4}\beta^2 = -\chi\rho\,, \tag{55}$$

$$\frac{\ddot{a}_1}{a_1} + \frac{\ddot{a}_3}{a_3} + \frac{\dot{a}_1\dot{a}_3}{a_1a_3} - \frac{m^2}{a_1^2} + \frac{3}{4}\beta^2 = -\chi\rho\,, \tag{56}$$

$$\frac{\ddot{a}_1}{a_1} + \frac{\ddot{a}_2}{a_2} + \frac{\dot{a}_1\dot{a}_2}{a_1a_2} - \frac{m^2}{a_1^2} + \frac{3}{4}\beta^2 = -\chi\rho\,, \tag{57}$$

$$\frac{\dot{a}_1\dot{a}_2}{a_1a_2} + \frac{\dot{a}_2\dot{a}_3}{a_2a_3} + \frac{\dot{a}_3\dot{a}_1}{a_3a_1} - \frac{3m^2}{a_1^2} - \frac{3}{4}\beta^2 = \chi\rho\,, \tag{58}$$

and

$$\frac{2\dot{a}_1}{a_1} = \frac{\dot{a}_2}{a_2} + \frac{\dot{a}_3}{a_3}\,. \tag{59}$$

In this case the values of a_1, a_2 and a_3 are the same as obtained in the vacuum model. However, it is not possible to obtain the values of ρ and β separately for this model. From Eq. (58), the value of ρ in terms of β is obtained as

$$\rho = p = \frac{1}{\chi}\left[-\frac{3}{4}\beta^2 - \frac{X^2}{m^6t^6}\right]. \tag{60}$$

The energy density satisfies the reality condition ($\rho > 0$) for $-\frac{3}{4}\beta^2 > \frac{x^2}{m^6t^6}$. Also, $\rho \to -\frac{3}{4}\beta^2$ as $t \to \infty$, which indicates that ρ is positive because β^2 is negative.

4. Some physical and geometrical features of the model

In this section we study the following physical and geometrical features of the models obtained in the preceding sections. The energy density (ρ) for the model (54) is obtained as

$$\rho = p = \frac{1}{\chi}\left[-\frac{3}{4}\beta^2 - \frac{X^2}{m^6 t^6}\right].$$

At initial epoch $t = 0$, the energy density $\rho \to \infty$ which indicates that the model possesses initial singularity. As $t \to \infty$, $\rho \to -(3/4)\beta^2$, this indicates that the model is guided by the gauge function β for any t except $t = 0$.

The scalar expansion θ is calculated as

$$\theta = \frac{1}{3}u^i_{;j} = \frac{3}{t}.$$

It is observed here that θ is always positive. Therefore, the model describes a physically realistic expanding model. At initial epoch $t = 0$, the scalar expansion θ diverges. The scalar expansion θ vanishes for large t.

The shear scalar σ^2 for the model (54) is obtained as

$$\sigma^2 = \frac{1}{2}\sigma^{ij}\sigma_{ij} = \frac{X^2}{m^6 t^6} + \frac{3}{2t^2} - \frac{1}{t} + \frac{1}{6}.$$

At initial epoch $t = 0$, shear scalar diverges. As t increases, σ^2 gradually decreases. However $\sigma^2 \to 1/6$ as $t \to \infty$.

Since $\lim_{t\to\infty} \sigma^2/\theta^2 \neq 0$, the model is not isotropic for large t.

The spatial volume of the model is obtained as

$$v = m^3 t^3.$$

At initial epoch $t = 0$, $v = 0$. As the time increases the volume increases and $v \to \infty$ as $t \to \infty$.

The deceleration parameter (q) is obtained as

$$q = -\frac{2}{3}.$$

It is evident that the model (54) represents an inflationary cosmological model.

5. Conclusion

In this paper we constructed the Bianchi type-V stiff-fluid cosmological model in the framework of Lyra manifold. We observe that the model (54) is inflationary, non-isotropic and possesses initial singularity.

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BIANCHIJEV KOZMOLOŠKI MODEL TIPA V U LYRINOJ MNOGOSTRUKOSTI

Razmatramo Bianchijev prostor-vrijeme tipa V uz prisutnost perfektne tekućine u okviru Lyrine mnogostrukosti i jednak tlak i gustoću energije ($p = \rho$). Raspravljaju se neke fizičke i geometrijske odlike modela.