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LRS Bianchi type-I Magnetized Dark Energy Models in a Scalar – Tensor Theory of Gravitation

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ABSTRACT
We have studied LRS Bianchi type-I magnetized cosmological models in the presence of scalar tensor theory proposed by Saez Ballester [1]. We assume that the dark energy (DE) is minimally interacting, has dynamical energy- density, anisotropic equation of state parameter (EoS). Exact solutions of Einstein's field equations are obtained by assuming a special law of variation for the mean Hubble parameter, which yields a constant value of the deceleration parameter. The geometrical and physical aspects for the models are also studied.

Introduction

Observational data like Ia supernovae suggest that the universe dominated by two dark component containing the dark energy (DE) and dark matter (DM). Dark energy with negative pressure is used to explain the present the cosmic accelerating expansion while dark matter used to explain galactic curves and large –scale structure formation.

The nature of the dark energy component of the universe [2-4] remains one of the deepest mysteries of cosmology. There is certainly no lack of candidates: cosmological constant, quintessence [5-7], k-essence [8-10], phantom energy [11-13]. Modifications of the Friedmann equation such as Cardassian expansion [14,15] as well as what might be derived from brane cosmology [16-18] have also been used to explain the acceleration of the universe. A particular case of the lin-ear equation of state has used in the cosmological con-text by Xanthopuolos [19], he considered space-times with two hyper surface orthogonal, space like, commuting killing fields.

After the discovery that the cosmic expansion is accelerating [3,20,2] and the first cosmic microwave background (CMB) radiation observation of a flat universe [21], the current standard model of cosmology implies the existence of dark energy which accounts for about 70% of the total energetic content of the universe, which ac-cording to the observations is spatially flat [22]. The nature of the dark energy is still a mystery [23]. Several models have been proposed to explain dark energy [24-32]. An alternative consists of to consider a phenomenological decaying dark energy density with continuous creation of matter [32] or photons [33,34].The dark energy might decay slowly in the course of the cosmic evolution and thus provide the source term for matter and radiation. Different such models have been discussed and strong constraints come from accurate measurements of the CMB. Although some authors [35] have suggested cosmological model with anisotropic and viscous dark energy in order to explain an anomalous cosmological observation in the cosmic microwave background (CMB) at the largest angles. The binary mixture of perfect fluid and dark energy was studied for Bianchi type-I and for Bianchi type-V [36] and [37] respectively. Akarsu *et al*. [38] have studied the Bianchi type-III with anisotropic dark energy.

Bianchi type models have been studied by several authors in an attempt to understand better the observed small amount of anisotropy in the universe. The same models have also been used to examine the role of certain anisotropic sources during the formation of the large-scale structures we see in the universe today. Some Bianchi cosmologies, for example, are natural hosts of large-scale magnetic fields and therefore, their study can shed light on the implications of cosmic magnetism for galaxy formation. The simplest Bianchi family that contains the flat FRW universe as a special case are the type-I space-times.

In this paper, we have discussed LRS Bianchi type-I cosmological model in the presence of magnetized dark energy with variable EoS parameter in Saez- Ballester scalar- tensor theory of gravitation. This paper is as follows:

In section 2, the metric and field equations are described. Section 3, deals with the solutions of the field equations . and concern with physical behaviour of the models .Finally conclusions are summarized in last section.

Metric and Field Equations

We consider the LRS Bianchi type-I metric in the following form:,

$$ds^2 = -dt^2 + a^2 dx^2 + b^2(dy^2 + dz^2) \quad (1)$$

where a and b are functions of cosmic time t only.

The energy momentum tensor for anisotropic dark energy with magnetic field is given by

$$T_j^i = T_j^i + T_j^i \quad (2)$$

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where

$${}^{\mathrm{DE}}T_j^i = (\rho_{\mathrm{ED}} + p_{\mathrm{ED}})u_i u^j + \mathrm{p}\mathrm{g}_j{}^i \quad (3)$$

where u^i is the flow vector satisfying

$$g_{ij}u^i u^j = -1 \quad (4)$$

T_j^i is the electromagnetic field tensor which is given by

$$T_{ij} = \frac{1}{4\pi}\left[F_{i\alpha}F_{j\beta}g^{\alpha\beta} - \frac{1}{4}g_{ij}F^{\alpha\beta}F_{\alpha\beta}\right] \quad (5)$$

where F_{ij} is the electromagnetic field tensor which satisfies the Maxwell equations

$$F_{[ij;\alpha]} = 0, (F^{ij}\sqrt{-g}) = 0 \quad (6)$$

In commoving coordinates, the incident magnetic field is taken along x-axis, with the help of Maxwell equations (6), the only non-vanishing component of F_{ij} is

$$F_{23} = \mathrm{const} = H. \quad (7)$$

With the help of equations (3)-(7),we can parameterize equation (2) as follows:

$$T^{ij} = \mathrm{dia}\left[-\rho - \frac{H^2}{8\pi b^4}, p_x - \frac{H^2}{8\pi b^4}, p_y + \frac{H^2}{8\pi b^4}, p_z + \frac{H^2}{8\pi b^4}\right]$$

$$T^{ij} = \mathrm{dia}\left[-(\rho + \frac{H^2}{8\pi b^4}), \rho\omega_x - \frac{H^2}{8\pi b^4}, \rho\omega_y + \frac{H^2}{8\pi b^4}, \rho\omega_z + \frac{H^2}{8\pi b^4}\right]$$

$$T^{ij} = \mathrm{diag}\left[-(\rho + \frac{H^2}{8\pi b^4}), \omega\rho - \frac{H^2}{8\pi b^4}, (\omega+\delta)\rho + \frac{H^2}{8\pi b^4}, (\omega+\delta)\rho + \frac{H^2}{8\pi b^4}\right] \quad (8)$$

Where ρ is the energy density of the fluid p_x, p_y, p_z are the pressures and $\omega_x, \omega_y, \omega_z$ are the directional EoS parameters along the x, y, z respectively $\omega(t) = p\rho$ is the deviation free EoS parameter of the fluid. We have parameterized the deviation from isotropy by setting $\omega_x = \omega$ and then introducing skewness parameter δ which is the deviation from ω along both *y* and *z*-axes.

The field equations given by Saez and Ballester [1] for the combined scalar and tensor fields are

$$R_{ij} - \frac{1}{2}Rg_{ij} - \varpi\phi^n(\phi,_i \phi,_j - \frac{1}{2}g_{ij}\phi,_k \phi^{,k}) = -T_{ij} \quad (9)$$

And the scalar field φ satisfies the equation

$$2\phi^n\phi^i_{,i} + n\phi^{n-1}\phi_{,k}\phi^{,k} = 0 \quad (10)$$

where ϖ and n are constants, T_{ij} is the energy momentum tensor of the matter and comma and semicolon denote partial and covariant differentiation respectively.

By adopting commoving coordinates the field equations (9) and (10), for the Bianchi type-I space-time, the field equations take the form

$$\frac{2a_4b_4}{a\,b} + \frac{b_4{}^2}{b^2} + \varpi\varphi^n\frac{\varphi_4{}^2}{2} = \rho + \frac{H^2}{b^4} \quad (11)$$

$$\frac{a_{44}}{a} + \frac{b_{44}}{b} + \frac{a_4b_4}{ab} + \varpi\varphi^n\frac{\varphi_4{}^2}{2} = -(\omega+\delta)\rho - \frac{H^2}{b^4} \quad (12)$$

$$\frac{2b_{44}}{b} + \frac{b_4{}^2}{b^2} - \varpi\varphi^n\frac{\varphi_4{}^2}{2} = -\omega\rho + \frac{H^2}{b^4} \quad (13)$$

Using equation (10) we get

$$\frac{\varphi_{44}}{\varphi_4} + \frac{a_4}{a} + 2\frac{b_4}{b} + \frac{n}{2}\frac{\varphi_4}{\varphi} = 0 \quad (14)$$

where a subscript 4 indicates differentiation with respect to t.

Solutions of the field equations

According to the proposed law, the variation of the mean Hubble parameter for the LRS Bianchi type-I metric may be given by

$$H = k(\mathrm{ab}^2)^{-\frac{n}{3}} \quad (15)$$

where $k > 0$ and $n \geq 0$ are constants. The spatial volume is given by

$$V = R^3 = \mathrm{ab}^2 \quad (16)$$

where *R* is the mean scale factor. The mean Hubble parameter *H* is given as

$$H = \frac{R_4}{R} = \frac{1}{3}\frac{V_4}{V} = \frac{1}{3}\left(\frac{a_4}{a} + 2\frac{b_4}{b}\right) \quad (17)$$

The directional Hubble parameters in the directions of *x,y and z* respectively may be defined as

$$H_x = \frac{a_4}{a} \text{ and } H_y = H_z = \frac{b_4}{b} \quad (18)$$

The volumetric deceleration parameter is

$$q = -RR_{44}R_4^{2} \quad (19)$$

On integrating, after equating (15) and (17), we obtain

$$ab^2 = c_1 e^{3kt} \text{ for } n = 0 \quad (20)$$

$$ab^2 = (nkt + c_2)^{\frac{3}{n}} \text{ for } n \neq 0 \quad (21)$$

Here c_1 and c_2 are positive constants of integration. Using (15) with (20) for $n = 0$, and with (21) for $n \neq 0$ mean Hubble parameters are

$$H = k \text{ for } n = 0 \quad (22)$$

and

$$H = k(nkt + c_2)^{-1} \text{ for } n \neq 0 \quad (23)$$

Using (20), (21) and (16) in (19), we get constant values for the deceleration parameter for the mean scale factor as:

$$q = n - 1 \text{ for } n \neq 0 \quad (24)$$

and

$$q = -1 \text{ for } n = 0 \quad (25)$$

The sign of q indicates whether the model accelerate or not. The positive sign of q $(i.e.\, n > 1)$ corresponds to decelerating models whereas the negative sign $-1 \leq q < 0$ for $0 \leq n < 1$ indicates acceleration .

Integration after subtracting equation (13) from (12) , we get

$$\left(\frac{a_4}{a} - \frac{b_4}{b}\right)\left(\frac{V}{\lambda}\right) = \exp\left\{-\int\left(\delta\rho + \frac{2H^2}{b^4}\right)\left(\frac{a_4}{a} - \frac{b_4}{b}\right)^{-1} dt\right\} \quad (26)$$

where λ is an integration constant. The integral term in above equation vanishes for

$$\delta = -\frac{2H^2}{\rho b^4} \quad (27)$$

Using equation (27) in equation (26) it follows that

$$\frac{a_4}{a} - \frac{b_4}{b} = \frac{\lambda}{V} \quad (28)$$

by considering (22) and (23) we obtain

$$\frac{a_4}{a} - \frac{b_4}{b} = \frac{\lambda}{c_1 \exp(3kt)} \text{ for } n = 0 \quad (29)$$

$$\frac{a_4}{a} - \frac{b_4}{b} = \frac{\lambda}{(nkt + c_2)^{3n}} \text{ for } n \neq 0 \quad (30)$$

Model for $n = 0$ $(q = -1)$

On integration of (29) and using (20) we get the following exact expression for the scale factors:

$$a = \left(\frac{c_1}{k_1{}^2}\right)^{\frac{1}{3}} \exp\left\{kt - \frac{2\lambda}{9c_1 k} e^{-3kt}\right\} \quad (31)$$

$$b = \left(\frac{c_1}{k_1}\right)^{\frac{1}{3}} \exp\left\{kt + \frac{\lambda}{9c_1 k} e^{-3kt}\right\} \quad (32)$$

where k_1 is positive constant of integration.. The spatial volume of the universe is found as

$$V = c_1 e^{3kt} \quad (33)$$

The directional Hubble parameters are

$$H_x = k + \frac{2\lambda}{3c_1} e^{-3kt} \quad (34)$$

$$H_y = H_z = k - \frac{\lambda}{3c_1} e^{-3kt} \quad (35)$$

The anisotropy parameter of the (Δ) is defined as

$$\Delta = \frac{1}{3}\sum_{i=1}^{3}\left(\frac{H_i - H}{H}\right)^2 \quad (36)$$

where H_i $(i = 1,2,3)$ represents the directional Hubble parameters in the direction $x, y,$ and z respectively.

By using (22) ,(24) , (35) in (36) , we get

$$\Delta = \frac{2}{9}\left[\frac{\lambda^2}{c_1{}^2 k^2} e^{-6kt}\right] \quad (37)$$

The expansion scalar θ is found as

$$\theta = 3k = 3H \quad (38)$$

The shear scalar σ^2 is found as

$$\sigma^2 = \frac{3}{2}\Delta H^2 = \frac{\lambda^2}{3{c_1}^2} e^{-6kt} \tag{39}$$

Using equation (14), the scalar field is found as

$$\varphi = \left[\frac{n+2}{2}\left(\frac{-\alpha}{3k} e^{-3kt} + \beta\right)\right]^{\frac{2}{n+2}} \tag{40}$$

Using equations (40) , (34) (35) in (11), we obtain the energy density for the model as

$$\rho = 3k^2 - \frac{\lambda^2}{3{c_1}^2} e^{-6kt} - H^2\left(\frac{k_1}{c_1}\right)^{\frac{4}{3}} \exp\left\{-4kt - \frac{4\lambda}{9c_1 k} e^{-3kt}\right\} + \frac{1}{2}\varpi\alpha^2 e^{-6kt} \tag{41}$$

Using equations (41) in (37), we obtain the deviation parameter as

$$\delta = -\frac{2H^2\left(\frac{k_1}{c_1}\right)^{4 3} \exp\left\{-4kt - \frac{4\lambda}{9c_1 k} e^{-3kt}\right\}}{3k^2 - \frac{\lambda^2}{3{c_1}^2} e^{-6kt} - H^2\left(\frac{k_1}{c_1}\right)^{\frac{4}{3}} \exp\left\{-4kt - \frac{4\lambda}{9c_1 k} e^{-3kt}\right\} + \frac{1}{2}\varpi\alpha^2 e^{-6kt}} \tag{42}$$

Using equation (34) (35),(41) and (42) in equation (12), we obtain the deviation –free parameter as

$$\omega = -\frac{3k^2 + \frac{\lambda^2}{3{c_1}^2} e^{-6kt} - H^2\left(\frac{k_1}{c_1}\right)^{\frac{4}{3}} \exp\left\{-4kt - \frac{4\lambda}{9c_1 k} e^{-3kt}\right\} - \frac{1}{2}\varpi\alpha^2 e^{-6kt}}{3k^2 - \frac{\lambda^2}{3{c_1}^2} e^{-3kt} - H^2\left(\frac{k_1}{c_1}\right)^{\frac{4}{3}} \exp\left\{-4kt - \frac{4\lambda}{9c_1 k} e^{-3kt}\right\} + \frac{1}{2}\varpi\alpha^2 e^{-6kt}} \tag{43}$$

Physical behaviour of the model for $n = 0\ (q = -1)$:

For this model $q = -1$ and $\frac{dH}{dt} = 0$, which implies the greatest value of the Hubble parameter and the fastest rate expansion of the universe. Thus, this model may represent the inflationary era in the early universe and the very late times of the universe.

The space approaches to isotropy in this model. $\Delta \to 0$ as $t \to \infty$.

The spatial volume *V* is finite at $t = 0$, expands exponentially as t increases and becomes infinitely large at $t = \infty$. The directional Hubble parameters H_x and $H_{y,z}$ are finite at $t = 0$.

The expansion scalar is constant throughout the evolution of the universe. The scalar is also finite at $t = 0$ .The anisotropy of the expansion decreases monotonically as *t* increases .The shear scalar is also finite at $t = 0$.

The ratio $\frac{\sigma^2}{\theta^2} \to 0$ as $t \to \infty$. Hence the model isotropizes for large value of the *t*.

The EoS parameter of the DE ω may begin in phantom $(\omega < -1)$ or quintessence $(\omega > -1)$ region and tends to -1 (cosmological constant $\omega = -1$) by exhibiting various patter as t increases.

Model for $n \neq 0$ and $q \neq -1$:

On integration (29) and using (21) we obtain the following exact expressions for the scale factors:

$$a = c_3^{23}(nkt + c_2)^{\frac{1}{n}}\left\{\exp\left(\frac{2\lambda}{3k(n-3)}\right)(nkt + c_2)^{\frac{n-3}{n}}\right\} \tag{44}$$

$$b = c_3^{-13}(nkt + c_2)^{\frac{1}{n}}\left\{\exp\left(\frac{-\lambda}{3k(n-3)}\right)(nkt + c_2)^{\frac{n-3}{n}}\right\} \tag{45}$$

where c_3 is the positive constant of integration. The spatial volume of the universe is found as

$$V = (nkt + c_2)^{\frac{3}{n}} \tag{46}$$

The directional Hubble parameters are found as

$$H_x = (nkt + c_2)^{-1}k + \frac{2\lambda}{3}(nkt + c_2)^{-3n} \tag{47}$$

$$H_y = H_z = (nkt + c_2)^{-1}k - \frac{\lambda}{3}(nkt + c_2)^{-3n} \tag{48}$$

Using (47), (48) in (36) we get

$$\Delta = \frac{2}{9}\frac{\lambda^2}{k^2}(nkt + c_2)^{2\left(1-\frac{3}{n}\right)} \tag{49}$$

For the anisotropy parameter of the expansion. The expansion and shear scalars are, respectively, found as

$$\theta = 3H = 3k(nkt + c_2)^{-1} \tag{50}$$

$$\sigma^2 = \frac{\lambda^2}{3}(nkt + c_2)^{-\frac{6}{n}} \tag{51}$$

Using equation (14), the scalar field is found as

$$\varphi = \left[\left(\frac{n+2}{2}\right)\left(\frac{P}{n-3}\right)(\text{nkt}+c_2)^{n-3n}\right]^{\frac{2}{n+2}} \quad (52)$$

Using (47), (48), (52) in (11) we get the energy density for the model as

$$\rho = 3k^2(\text{nkt}+c_2)^{-2} - \frac{1}{3}\lambda^2(\text{nkt}+c_2)^{-\frac{6}{n}} - H^2 c_{3^{4s}}(\text{nkt}+c_2)^{-4n} \exp\left\{\frac{4\lambda}{3(n-3)k}(\text{nkt}+c_2)^{\frac{n-3}{n}}\right\} + \frac{1}{2}\varpi P^2 k^2(\text{nkt}+c_2)^{-\frac{6}{n}} \quad (53)$$

Using (53) in (37), we get the deviation parameter as

$$\delta = \frac{2H^2 c_{3^{4s}}(\text{nkt}+c_2)^{\frac{-4}{n}}\left\{\exp\left(\frac{4\lambda}{3k(n-3)}\right)(\text{nkt}+c_2)^{\frac{n-3}{n}}\right\}}{3k^2(\text{nkt}+c_2)^{-2} - \frac{1}{3}\lambda^2(\text{nkt}+c_2)^{-\frac{6}{n}} - H^2 c_{3^{4s}}(\text{nkt}+c_2)^{-4n}\exp\left\{\frac{4\lambda}{3(n-3)k}(\text{nkt}+c_2)^{\frac{n-3}{n}}\right\} + \frac{1}{2}\varpi P^2 k^2(\text{nkt}+c_2)^{-\frac{6}{n}}} \quad (54)$$

Using (47),(48), (52) and (54) in (12) we get the deviation- free parameter as

$$\omega = \frac{(3-2n)k^2(\text{nkt}+c_2)^{-2} + \frac{\lambda^2}{3}(\text{nkt}+c_2)^{-6n} - H^2 c_{3^{4s}}\left[(\text{nkt}+c_2)^{-43}\exp\left\{\frac{4\lambda}{3(n-3)k}(\text{nkt}+c_2)^{\frac{n-3}{n}}\right\}\right] - \frac{1}{2}\varpi P^2 k^2(\text{nkt}+c_2)^{-\frac{6}{n}}}{3k^2(\text{nkt}+c_2)^{-2} - \frac{1}{3}\lambda^2(\text{nkt}+c_2)^{-\frac{6}{n}} - H^2 c_{3^{4s}}(\text{nkt}+c_2)^{-4n}\exp\left\{\frac{4\lambda}{3(n-3)k}(\text{nkt}+c_2)^{\frac{n-3}{n}}\right\} + \frac{1}{2}\varpi P^2 k^2(\text{nkt}+c_2)^{-\frac{6}{n}}} \quad (55)$$

Physical behaviour of the model for $n \neq 0 \ (q \neq -1)$

The universe accelerates for $0 < n < 1$, decelerates for $n > 1$ and expands with constant velocity for $n = 1$. The spatial volume V is finite at $t = 0$ and becomes infinitely large as $t \to \infty$. In this model , the average scale factor $R = (\text{nkt}+c_2)^{\frac{1}{n}}$. It has point singularity at $t = -\frac{c_2}{\text{nk}}$. The Hubble parameters H_x, H_y, H_z and H are infinite at this point but here the spatial volume vanishes. Also the mean Hubble parameter expansion scalar θ and shear scalar σ^2 are constant at $t = 0$ and zero at $t = \infty$ Moreover, as $t \to 0$

$$A(t) \to k^{\frac{-2}{3}}(c_2)^{\frac{1}{n}}\exp\left\{\frac{2\lambda}{3(n-3)k}(c_2)^{\frac{n-3}{n}}\right\}$$ and

$$B(t) \to k^{\frac{1}{3}}(c_2)^{\frac{1}{n}}\exp\left\{\frac{-\lambda}{3(n-3)k}(c_2)^{\frac{n-3}{n}}\right\}.$$

As $t \to \infty$, $A(t) \to \infty, B(t) \to \infty$.The anisotropy of the expansion $\Delta \to \text{constant}$ as $t \to 0$. $\Delta \to \text{null}$ as $t \to \infty$ for $m > 3$. When $m > 3$, $\Delta \to \text{const.}$ as $t \to 0$ while $\Delta \to \infty$ as $t \to \infty$.

The EoS parameter of the DE ω may begin in phantom $(\omega < -1)$ or quintessence $(\omega > -1)$ region and tends to -1 (cosmological constant $\omega = -1$) by exhibiting various patter according to the choice of the parameter.

The ratio $\frac{\sigma^2}{\theta^2} \to 0$ as $t \to \infty$. Hence the model isotropizes for large value of the t (for $0 < n < 3$).

Conclusion

LRS Bianchi Type –I cosmological models with magnetized anisotropic dark energy in a scalar tensor theory have been constructed in general relativity. A special law has been assumed for the deviation from isotropic EoS. Exact solutions of Einstein's field equations have been obtained by assuming a special law of variation for the Hubble parameter which yields a constant value of the deceleration parameter.

The anisotropy of the expansion can mildly or totally isotropize in relatively earlier times of the universe. Nevertheless, it converges to a nonzero constant value for the later times of the universe in all models.

The energy density of the fluid ρ, the deviation- free EoS parameter ω and the deviation parameter δ are dynamical.

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