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Bianchi Type-III Universe with Anisotropic Dark Energy and Special form of Deceleration Parameter

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Abstract: The present study deals with Bianchi type-III cosmological models with anisotropic dark energy and special form of deceleration parameter. To have a general description of an anisotropic dark energy component, a phenomenological parameterization of dark energy in terms of its equation of state (EoS) ω and two skewness parameters (δ, γ) have been introduced. The geometrical and physical behaviour of the models are also discussed.

Keywords: Bianchi type-III space-time, Perfect fluid and anisotropic dark energy, special form of deceleration parameter.

I. INTRODUCTION

Recent observations of Type Ia supernovae (SNeIa) [1] indicate that the current universe is not only expanding but also accelerating. These results, when combined with the observations of cosmic microwave background (CMB) [2] and large scale structure (LSS)[3], strongly suggest that the Universe is spatially flat and dominated by an exotic component with large negative pressure, referred to as dark energy [4]. The first year result of the Wilkinson Microwave Anisotropy Probe (WMAP) shows that dark energy occupies about 73% of the energy of our Universe, and dark matter about 23%. The usual baryon matter which can be described by our known particle theory occupies only about 4% of the total energy of the Universe.

The recent detection of Integrated Sachs-Wolfe effect [5] also gives a strong and independent support to dark energy. In principle, any physical field with positive energy density and negative pressure, which violates the strong energy condition, may cause the dark energy effect of repulsive gravitation.

The major problem in cosmology is to identify the form of dark energy that dominates the universe today whether it is phantom energy, quintessence, simply Λ or something else. Also one can try Chaplygin gas model [6, 7] with equation of state (EoS) $p = -B/\rho$, as it generates negative pressure, where p and ρ are respectively the pressure and energy density and B is a positive constant.The dark energy might be due to

(a) quintessence field if $-1 < \omega < -\frac{1}{3}$

(b) cosmological constant Λ if $\omega = -1$, or

(c) phantom field if $\omega < -1$.

In the above classification, the equation of state parameter ω plays the role of dark energy parameter.

Today we can examine not only when the cosmic acceleration began and the current value of the deceleration parameter, but also how the acceleration (the deceleration parameter) varies with time. In a recent paper, Li et al. [8] has examined the current acceleration of the universe by the largest and latest SNIa sample (Union2), baryonic acoustic oscillation (BAO) and cosmic microwave background (CMB) radiation together. They conclude that once the systematic error is taken into account, two different subsamples of Union2 along with BAO and CMB all favor an increase of the present cosmic acceleration. The authors also give plots they obtained for the change of the deceleration parameter q with redshift z < 2.

After the discovery of the late time acceleration of the universe, many authors have used CDP to obtain cosmological models in the context of dark energy (DE) in general relativity and some other modified theories of gravitation such as f(R) theory within the framework of spatially isotropic and anisotropic space-times. However, generalizing CDP assumption would allow us to construct more precise cosmological models.

Many authors [9], [10] proposed a linearly varying deceleration parameter (LVDP), which can be used in obtaining accelerating cosmological solutions. As a special case, LVDP also covers the special law of variation for Hubble parameter, which yields constant deceleration parameter (CDP) models of the universe, presented by Berman [11, 12].

By choosing a particular form of the deceleration parameter q, which gives an early deceleration and late time acceleration for dust dominated model, [13] shows that this sign flip in q can be obtained by a simple trigonometric potential.

The quintessence model [14] with a minimally coupled scalar field by taking a special form of decelerating parameter q in such a way that which provides an early deceleration and late time acceleration for barotropic fluid and Chaplygin gas dominated models.

Motivated from the studies outlined above we choose a form of q as a function of the scale factor a so that it has the desired property of a signature flip.

In recent years various form of time dependent ω have been used for variable Λ models [19, 20]. Recently Ray et al [21], Akarsu and Kilinc [22] and Yadav et al. [23] have studied dark energy model with variable EoS parameter.

Spatially homogeneous and anisotropic cosmological models play a significant role in description of the large scale behavior of universe. Bianchi type III cosmological model in presence of dark

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energy have been studied in general relativity by numerous authors. Lorentz [24] has presented a model with dust and cosmological constant. Chakraborty and Chakraborty have given a bulk viscous cosmological model with variable G and Λ [25]. Singh et al [26] have investigated a model with variable G and Λ in presence of perfect fluid by assuming a conservation law of energy-momentum tensor. Recently, Tiwari [27] has studied a model in presence of perfect fluid and time dependent Λ with constant deceleration parameter. Bali and Tinkar [28] have investigated a model in the presence of bulk viscous borotropic fluid with variable G and Λ. Unlike Robertson-Walkar metric, Bianchi type III can admit a dark energy that yields an anisotropic EoS parameter according to their characteristics. The cosmological data from the large scale structure [3] and type Ia supernova [1, 2] observations do not rule out the possibility of anisotropic dark energy either [29, 30].

In the present paper, the Bianchi type-III cosmological models with anisotropic dark energy and special form of deceleration parameter have been studied. To have a general description of an anisotropic dark energy component, a phenomenological parameterization of dark energy in terms of its equation of state (EoS) ω and two skewness parameters (δ, γ) have been introduced. The geometrical and physical behavior of the models is also discussed.

II. METRIC AND FIELD EQUATIONS

The homogenous and anisotropic Bianchi-Type-III space-time can be written as

$$ds^2 = dt^2 - A(t)^2 dx^2 - B(t)^2 e^{-2\alpha x} dy^2 - C(t)^2 dz^2 \quad , \tag{2.1}$$

where $A(t)$, $B(t)$ and $C(t)$ are functions of cosmic time t only and $\alpha \neq 0$ is a constant.
In natural units $(8\pi G = 1, c = 1)$, the Einstein's field equations are

$$G_{ij} = R_{ij} - \frac{1}{2} g_{ij} R = -T_{ij} \quad , \tag{2.2}$$

where T_{ij} is the energy momentum tensor of dark energy.
Since here we are dealing only with an anisotropic fluid, we may write down the energy momentum tensor of the fluid in the following form

$$\begin{aligned} T_i^j &= diag[\rho, \quad -p_x, \quad -p_y, \quad -p_z] \\ &= diag[1, \quad -\omega_x, \quad -\omega_y, \quad -\omega_z]\rho \\ &= diag[1, \; -\omega, \; -(\omega+\delta), \; -(\omega+\gamma)]\rho \quad , \end{aligned} \tag{2.4}$$

where g_{ij} is the metric potential with $g_{ij}u^i u^j = 1$ where u^i is the flow vector: R_{ij} is the Ricci tensor; R is the Ricci scalar; ρ is the energy density; ω is the deviation-free EoS Parameter of the dark energy and one can parametrized the deviation from isotropy by setting $\omega_x = \omega$ and then introducing skewness parameters δ and γ that are the deviations from ω respectively on both the

y and z axes respectively. Here ω and γ are not necessarily constants and can be functions of the cosmic time *t*.

The Einstein's field equations (2.2) for metric (2.1) with the help of equations (2.4) can be written as

$$\frac{\dot{A}\dot{B}}{AB}+\frac{\dot{A}\dot{C}}{AC}+\frac{\dot{B}\dot{C}}{BC}-\frac{\alpha^2}{A^2}=\rho \ , \tag{2.5}$$

$$\frac{\ddot{B}}{B}+\frac{\ddot{C}}{C}+\frac{\dot{B}\dot{C}}{BC}=-\omega\rho \ , \tag{2.6}$$

$$\frac{\ddot{A}}{A}+\frac{\ddot{C}}{C}+\frac{\dot{A}\dot{C}}{AC}=-(\omega+\delta)\rho \, , \tag{2.7}$$

$$\frac{\ddot{A}}{A}+\frac{\ddot{B}}{B}+\frac{\dot{A}\dot{B}}{AB}=-(\omega+\gamma)\rho \, , \tag{2.8}$$

$$\alpha\left(\frac{\dot{A}}{A}-\frac{\dot{B}}{B}\right)=0 \, . \tag{2.9}$$

where dot $(\cdot)$ indicates the derivative with respect to *t*.

III. ISOTROPIZATION AND THE SOLUTION

The directional Hubble parameters in the direction of x, y and z for the Bianchi type-III metric defined in equation (2.1) are defined as

$$H_x=\frac{\dot{A}}{A}, \quad H_y=\frac{\dot{B}}{B} \quad \text{and } H_z=\frac{\dot{C}}{C}. \tag{3.1}$$

The mean Hubble parameter is given by

$$H=\frac{1}{3}\frac{\dot{V}}{V}=\frac{1}{3}\left(\frac{\dot{A}}{A}+\frac{\dot{B}}{B}+\frac{\dot{C}}{C}\right), \tag{3.2}$$

where $V = ABC$ is the spatial volume of the universe.
The anisotropy parameter of the expansion is defined as

$$\Delta=\frac{1}{3}\sum_{i=1}^{3}\left(\frac{H_i-H}{H}\right)^2 . \tag{3.3}$$

where $H_i\,(i=1,2,3)$ represents the directional Hubble parameters in the directions of x, y and z respectively.
Solving equation (2.9), we get

$$B=c_1A, \tag{3.4}$$

where c_1 is the positive constant of integration. Substituting equation (3.4) in equation (2.7), and subtract it from the equation (2.6), the skewness parameter on the *y*-axis is obtained as

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$$\delta = 0. \tag{3.5}$$

Now, using equations (3.1), (3.2) and (3.4) in equation (3.3), equation (3.3) is reduced to

$$\Delta = \frac{2}{9}\frac{1}{H^2}\left(H_x - H_z\right)^2. \tag{3.6}$$

Substituting equations (3.4) and (3.5), the field equations (2.5)-(2.9) reduces to

$$\frac{\dot{A}^2}{A^2} + 2\frac{\dot{A}\dot{C}}{AC} - \frac{\alpha^2}{A^2} = \rho \ , \tag{3.7}$$

$$\frac{\ddot{A}}{A} + \frac{\ddot{C}}{C} + \frac{\dot{A}\dot{C}}{AC} = -\omega\rho \, , \tag{3.8}$$

$$2\frac{\ddot{A}}{A} + \frac{\dot{A}^2}{A^2} = -(\omega + \gamma)\rho \, . \tag{3.9}$$

Subtracting equation (3.8) from equation (3.9) and solving the resulting equation gives

$$H_x - H_z = \frac{\dot{A}}{A} - \frac{\dot{C}}{C} = \frac{\lambda}{V} + \frac{1}{V}\int\left(\frac{\alpha^2}{A^2} - \gamma\rho\right)Vdt \ , \tag{3.10}$$

where λ is real constant of integration.
Using equation (3.10) in equation (3.6), the anisotropy parameter becomes

$$\Delta = \frac{2}{9}\frac{1}{H^2}\left[\lambda + \int\left(\frac{\alpha^2}{A^2} - \gamma\rho\right)Vdt\right]^2 V^{-2}. \tag{3.11}$$

The integral term in equation (3.11) vanishes for

$$\gamma = \frac{\alpha^2}{\rho A^2}. \tag{3.12}$$

The energy momentum tensor for anisotropic dark energy becomes

$$T_j^i = diag\left[1, -\omega, -\omega, -\omega - \frac{\alpha^2}{\rho A^2}\right]\rho. \tag{3.13}$$

The anisotropy parameter becomes

$$\Delta = \frac{2}{9}\frac{\lambda^2}{H^2}V^{-2}. \tag{3.14}$$

Also equation (3.10) reduces to

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$$H_x - H_z = \frac{\lambda}{ABC} \tag{3.15}$$

Now, using equations (3.12) and (3.13) in the field equations (3.7)-(3.9), one can obtain the reduced field equations as

$$\frac{\dot{A}^2}{A^2} + 2\frac{\dot{A}\dot{C}}{AC} = \rho + \frac{\alpha^2}{A^2} = (1+\gamma)\rho \ , \tag{3.16}$$

$$\frac{\ddot{A}}{A} + \frac{\ddot{C}}{C} + \frac{\dot{A}\dot{C}}{AC} = -\omega\rho \ , \tag{3.17}$$

$$2\frac{\ddot{A}}{A} + \frac{\dot{A}^2}{A^2} = -\omega\rho \ . \tag{3.18}$$

Now, these are three linearly independent equations (3.16)-(3.18) with four unknowns (A, C, ρ *and* ω). We need extra condition to solve the field equations completely.
To do that we assumea special form of deceleration parameter as

$$q = -\frac{\ddot{a}a}{\dot{a}^2} = -1 + \frac{k}{1+a^k} \ , \tag{3.19}$$

where a is mean scale factor of the universe , $k > 0$ is constant. This law has been recently proposed bySingha andDebnath[14] for FRW metric.From figure (i) we have seen that q decreases from $+1$ to -1 for evolution of the universe.Adhav et al. [31] has extended this law for Bianchi type-I,III,V,VI0 and Katowaki-sachs cosmological models with dynamical equation of state (EoS) parameter.

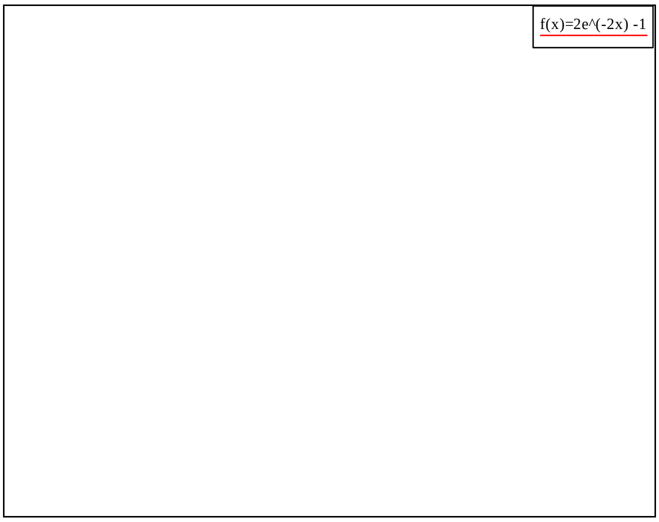

Fig. (i) The variation of q vs. t for $k = 2$.

We know that the universe has

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(i) decelerating expansion if $q > 0$.

(ii) an expansion with constant rate if $q = 0$.

(iii) accelerating power law expansion if $-1 < q < 0$.

(iv) exponential expansion (or deSitter expansion) if $q = -1$.

(v) super- exponential expansion if $q < -1$, [16, 17, 18] .

From (3.19) we obtain the Hubble parameter as

$$H = \frac{\dot{a}}{a} = m\left(1 + a^{-k}\right) \quad , \tag{3.20}$$

where m is an integration constant.

Now by integrating above equation, one can obtain the mean scale factor as

$$a = \left(e^{mkt} - 1\right)^{1/k}, \tag{3.21}$$

which gives the average scale factor a in the explicit form of cosmic time t.

With equation (3.21), choosing $m = 1$ the spatial volume is given by

$$V = a^3 = \left(e^{kt} - 1\right)^{3/k}. \tag{3.22}$$

Subtracting equation (3.17) from (3.18) and using (3.2), we get

$$\frac{\frac{d}{dt}\left(\frac{\dot{A}}{A} - \frac{\dot{C}}{C}\right)}{\left(\frac{\dot{A}}{A} - \frac{\dot{C}}{C}\right)} + \frac{\dot{V}}{V} = 0 \quad , \tag{3.23}$$

which on integrating gives

$$\left(\frac{\dot{A}}{A} - \frac{\dot{C}}{C}\right) = \frac{c_2}{V} \quad , \tag{3.24}$$

where c_2 is constant of integration.

After using (3.22) in (3.24) and integrating and taking the help of (3.2) and (3.4),we obtain the scale factors as

$$A(t) = \left(c_1 c_2^5\right)^{\frac{1}{3}} \left(e^{kt} - 1\right)^{1/k}.\exp\left\{-\frac{1}{9}\left(1 - e^{-kt}\right)^{3/k}\left(e^{kt} - 1\right)^{-3/k} {}_2F_1\left(\frac{3}{k}, \frac{3}{k}; \frac{k+3}{k}; e^{-kt}\right)\right\}. \tag{3.25}$$

$$B(t) = \left(\frac{c_2}{c_1^2}\right)^{\frac{1}{3}} \left(e^{kt} - 1\right)^{1/k}.\exp\left\{-\frac{1}{9}\left(1 - e^{-kt}\right)^{3/k}\left(e^{kt} - 1\right)^{-3/k} {}_2F_1\left(\frac{3}{k}, \frac{3}{k}; \frac{k+3}{k}; e^{-kt}\right)\right\}. \tag{3.26}$$

$$C(t) = \left(c_1 c_2^2\right)^{\frac{1}{3}} \left(e^{kt} - 1\right)^{1/k}.\exp\left\{\frac{2}{9}\left(1 - e^{-kt}\right)^{3/k}\left(e^{kt} - 1\right)^{-3/k} {}_2F_1\left(\frac{3}{k}, \frac{3}{k}; \frac{k+3}{k}; e^{-kt}\right)\right\}. \tag{3.27}$$

Using equations (3.25) to (3.27) in (3.1), we obtain the directional Hubble parameter in the direction of of x, y and z axis as

$$H_x = \frac{\dot{A}}{A} = \frac{1}{3}\left(e^{kt}-1\right)^{-3/k} + \frac{e^{kt}}{\left(e^{kt}-1\right)} \quad . \qquad (3.28)$$

$$H_y = \frac{\dot{B}}{B} = \frac{1}{3}\left(e^{kt}-1\right)^{-3/k} + \frac{e^{kt}}{\left(e^{kt}-1\right)} \quad . \qquad (3.29)$$

$$H_z = \frac{\dot{C}}{C} = -\frac{2}{3}\left(e^{kt}-1\right)^{-3/k} + \frac{e^{kt}}{\left(e^{kt}-1\right)} \quad . \qquad (3.30)$$

The mean Hubble parameter for the given metric is found to be

$$H = \frac{1}{(1-e^{-kt})} \quad . \qquad (3.31)$$

Using (3.28), (3.30) and (3.31) in (3.6), we obtain the anisotropy parameter as

$$\Delta = \frac{2}{9}\frac{\left(1-e^{-kt}\right)^2}{\left(e^{kt}-1\right)^{6/k}} \quad . \qquad (3.32)$$

The value of energy density is found by using the scale factors in equation (3.16) as

$$\rho = \left\{ \frac{3}{(1-e^{-kt})^2} - \frac{1}{3(e^{kt}-1)^{6/k}} - \frac{\alpha^2 \exp[\frac{2}{9}(1-e^{-kt})^{3/k}(e^{kt}-1)^{-3/k}\, {}_2F_1\left(\frac{3}{k},\frac{3}{k};\frac{k+3}{k};e^{-kt}\right)]}{(c_1c_2^5)^{2/3}(e^{kt}-1)^{2/k}} \right\}. \qquad (3.33)$$

The deviation-free part of the anisotropic EoS parameter may be obtained by using (3.25) and (3.33) in (3.18) as

$$\omega = -\left\{ \frac{\frac{2k}{(1-e^{-kt})} + \frac{(3-2k)}{(1-e^{-kt})^2} + \frac{4e^{-3t}}{3(1-e^{-kt})^{\frac{k+3}{k}}} - \frac{4k}{9(1-e^{-kt})^{t(\frac{2k+3}{3})}} + \frac{2}{9(e^{kt}-1)^{2(\frac{2}{k}+\frac{1}{3})}} + \frac{1}{9(e^{kt}-1)^{6/k}}}{\frac{3}{(1-e^{-kt})^2} - \frac{1}{3(e^{kt}-1)^{6/k}} - \frac{\alpha^2 \exp[\frac{2}{9}(1-e^{-kt})^{3/k}(e^{kt}-1)^{-3/k}\, {}_2F_1\left(\frac{3}{k},\frac{3}{k};\frac{k+3}{k};e^{-kt}\right)]}{(c_1c_2^5)^{2/3}(e^{kt}-1)^{2/k}}} \right\}. \qquad (3.34)$$

Since $\delta = 0$, deviation parameter γ can be obtained by using equations (3.25) and (3.33) in equation (3.11) as

$$\gamma = \left\{ \frac{\alpha^2 (c_1c_2^5)^{-2/3}(e^{kt}-1)^{-2/k} \exp[\frac{2}{9}(1-e^{-kt})^{3/k}(e^{kt}-1)^{-3/k}\, {}_2F_1\left(\frac{3}{k},\frac{3}{k};\frac{k+3}{k};e^{-kt}\right)]}{3(1-e^{-kt})^{-2} - \frac{1}{3}(e^{kt}-1)^{-6/k} - \alpha^2 (c_1c_2^5)^{-2/3}(e^{kt}-1)^{-2/k} \exp[\frac{2}{9}(1-e^{-kt})^{3/k}(e^{kt}-1)^{-3/k}\, {}_2F_1\left(\frac{3}{k},\frac{3}{k};\frac{k+3}{k};e^{-kt}\right)]} \right\}. \qquad (3.35)$$

The expansion scalar $\theta = 3H$ is found as

$$\theta = \frac{3}{\left(1-e^{-kt}\right)} . \qquad (3.36)$$

The shear scalar $\sigma^2 = \frac{1}{2}\left(\sum_{i=1}^{3} H_i^2 - 3H^2\right) = \frac{3}{2}\Delta H^2$ is found as

$$\sigma^2 = \frac{1}{3}\frac{1}{\left(e^{kt}-1\right)^{6/k}} .(3.37)$$

IV.PHYSICAL BEHAVIOUR OF THE MODEL

The spatial volume is finite at $t=0$. It expands exponentially as t increases and becomes infinitely large as $t \to \infty$. The directional Hubble parameters are infinite at $t=0$ and finite at $t=\infty$. The expansion scalar $\theta = 3H = 3$, is constant throughout the evolution of the universe.

The energy density of the DE component $\rho \to \infty$ as $t \to 0$ and as $t \to \infty$, the energy density $\rho \to 3 > 0$ i.e. finite.

The anisotropy of the expansion $\Delta \to 0$ as $t \to 0$ and decreases to null exponentially as t increases. Thus the space approaches to isotropy in this model. The deviation parameter $\delta = 0$ throughout and $\gamma \to \infty$ as $t \to 0$ and as $t \to \infty$, $\gamma \to 0$ is finite.

Also at rest when $t \to 0$, the EoS parameter ω tends to infinity and as time increases, the EoS parameter ω tends to -1 which gives the strong support to the existence of dark energy. For this model the shear scalar $\sigma^2 \to \infty$ as time $t \to 0$ and decreases to null as time increases.

V.CONCLUSION

In the present paper, the Bianchi type-III cosmological models with anisotropic dark energy and special form of deceleration parameter have been studied. The geometrical and physical behavior of the models is also discussed.

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