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Research Article

INTERACTING DARK FLUIDS IN BIANCHI TYPE-I UNIVERSE WITH VARIABLE DECELERATION PARAMETER

Mete V. G[1]., Bokey V. D[2] and Bawane V. S[3]

[1]Department of Mathematics, R.D.I.K & K.D. College, Badnera- Amravati, India
[2]Department of Mathematics, Nehru Mahavidyalaya, Nerparsopant Dist. Yavatmal, India
[3]Department of Mathematics, Mahatma Fule Arts, Comm. & S. C. Chaudhari Science College, Warud, Dist. Amravati, Maharashtra, India

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A B S T R A C T

The present work deals with a Bianchi Type-I universe filled with interacting dark matter and holographic dark energy in the frame of Einstein theory of relativity. To obtain the cosmological solutions, we used variable deceleration parameter in the form $a(t)=[\sinh(\alpha t)]^{\frac{1}{n}}$, where α and n are constants.The physical and geometrical properties of the model are obtained and discussed in details.

INTRODUCTION

The present acceleration of the universe has been well established through numerous and complementary cosmological observations. The recent cosmological observations of type Ia supernovae (SNIa) (Riess *et al.* [54]; Perlmutter *et al.* [45]) indicates that currently universe is accelerating. When these results combines with the observations of cosmic microwave background (CMB) (Bennett *et al.* [16]; Spergel *et al.* [64]) and also the large scale structure (LSS)(Tegmark *et al.* [66], [67]), indicates that spatially flat universe is dominated by an exotic component with strong negative pressure called as dark energy (Weinberg [70]; Carroll [22]; Peebles and Ratra [44]; Padmanabhan [43]). Many authors have been studied a special class of interacting models in which holographic dark energy is allowed to interact with dark matter (Gong[29]; Gong and Zhang[28]; Wang *et al.*[69]; Nojiri and Odintsov[40]; Guo *et al.* [31]; Banerjee and Pavon[15]; Zimdahl and Pavon[75]; Zimdahl[76]). Also Guo *et al.*[32], have shown that the proposal of interacting dark energy is compatible with current observations of the SNIa and CMB data.

Bianchi type dark energy models with usual perfect fluid have been studied by Akarsu and Kilinc [7], Yadav *et al.* [73], Adhav *et al.* [1], Saha and Yadav [57]. Recently a Bianchi type- IX minimally interacting holographic dark energy model with linearly varying deceleration parameter in scalar tensor theory of gravitation has been studied by D. R. K. Reddy *et al.* [52]. A viable holographic dark energy model was constructed by Li [38] by using the principle of quantum gravity theory (Susskind [65]) and also widely studied by several authors. In particular, Sarkar and Mohanta [58] have discussed the evolution of holographic dark energy in Bianchi type-I universe with constant deceleration parameter whereas Sarkar [59] has investigated holographic dark energy model in Bianchi type-I universe with linearly varying models of universe. Cai Rong-Gen *et al.* [21] has studied a model in which phantom dark energy is coupled to dark matter phenomenologically introducing a coupled term to the equations of motion of dark energy and dark matter. Setare [63] has studied holographic dark energy model in Brans-Dicke theory. Bianchi type-V minimally interacting holographic dark energy model in scalar tensor theory of gravitation has been investigated by Kiran *et al.* [36]. Adhav *et al.* [2] have constructed interacting holographic dark energy models in Bianchi type space-time. Sarkar ([59], [60], [61]) have studied non interacting holographic dark energy with linearly varying deceleration parameter in Bianchi type-IandV universe and interacting holographic dark energy in Bianchi type-II respectively.

Several candidates for dark energy namely the quintessence scalar field models (Wetterich [72]; Ratra and Peebles [49]),

Corresponding author:* **Mete V. G
Department of Mathematics, R.D.I.K & K.D. College, Badnera- Amravati, India

K-essence (Chiba *et al.* [24]; Armendariz-Picon *et al.* [11], [12]) tachyon field (Sen [62]; Padmanabhan and Chaudhury [42]), quintom (Elizalde *et al.* [27]; Anisimov *et al.* [10]), the dark energy models including Chaplygin gas (Kamenshchik *et al.* [35]; Bento *et al.* [17]) etc. Recently a different dark energy cosmologies (isotropic) with early deceleration and late time acceleration have reviewed by Bamba *et al.*[14]. They have studied *f* (R) gravity, *f* (R, T) gravity, scalar field theory holographic dark energy, coupled dark energy and $\wedge$CDM cosmological models representing the accelerating expansion with quintessence/phantom nature in details along with cosmological tests. Bianchi type-III cosmological model in *f* (R, T) theory of gravity was studied by D. R. K. Reddy *et al.* [50]. Recently Reddy *et.al.*[51] have studied Bianchi type-V modified holographic Ricci dark energy model in the modified theory of gravitation in Lyra geometry.

In order to obtain exact solutions of Einstein field equations, many authors assumes various physical conditions and several of them used conditions on deceleration parameter. A law of variation for Hubble parameter which yields constant deceleration parameter models of universe was proposed by Berman [18]. Akarsu and Kilinc [7], Pradhan *et al.* [47] and Adhav *et al.* [3] have extended this law for Bianchi type. Kumar and Singh [37] and Pradhan *et al.* [47] has applied the law presented by Berman to Bianchi type-I universe by allowing anisotropy in the pressure in the fluid. Yadav *et al.*[74] and Adhav *et al.* ([4], [5]) have been extended this law for Bianchi type -V and Kantowaski-Sachs space-time respectively.

The motivation to choose time dependent deceleration parameter is behind the fact that the universe has accelerated expansion at present as observed in the observation of Riess *et al.*[54], Perlmutter *et al.* [46], Tonry *et al.* [68], Riess *et al.* [55], Clocchiatti *et al.* [25] and cosmic microwave background (CMB) anisotropies, Bennett *et al.* [16], Bernardis *et al.* [19], Hanany *et al.* [33] and decelerated expansion in the past. Again the transition redshift from decelerated expansion to accelerated expansion is about 0.5. The deceleration parameter must show signature flipping as the universe was decelerating in the past and accelerating at present time, Padmanabhan and Roychowdhury [41], Amendola [9], Riess *et al.* [53]. In general deceleration parameter is not a constant but a time variable.

Motivated by the above discussion, in this paper, we consider spatially homogeneous and anisotropic Bianchi type-I universe filled with interacting dark matter and holographic dark energy.

Metric and field equations

The Bianchi Type-I line element can be written as

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

where *A, B, C* are cosmic scale factors.

The Einstein field equations (with natural limit 8πG=1 and c=1) are

$$R_{ij} - \frac{1}{2}g_{ij}R = -\left({}^{m}T_{ij} + {}^{\wedge}T_{ij}\right), \tag{2}$$

where ${}^{m}T_{ij} = \rho_m u_i u_j$ and

$${}^{\wedge}T_{ij} = (\rho_\wedge + p_\wedge)u_i u_j - g_{ij}p_\wedge, \tag{3}$$

are energy momentum tensors for dark matter (pressureless, i.e. $\omega_m = 0$) and holographic dark energy. The quantities ρ_m, $\rho_\wedge$ and $p_\wedge$ are density of dark matter, energy density and pressure of holographic dark energy respectively.

The Einstein field equations (2) for the metric (1), using equations (3) can be written as

$$\frac{\dot{A}\dot{B}}{AC} + \frac{\dot{B}\dot{C}}{BC} + \frac{\dot{A}\dot{C}}{AC} = \rho_m + \rho_\wedge, \tag{4}$$

$$\frac{\ddot{A}}{A} + \frac{\ddot{B}}{B} + \frac{\dot{A}\dot{B}}{AB} = -p_\wedge, \tag{5}$$

$$\frac{\ddot{B}}{B} + \frac{\ddot{C}}{C} + \frac{\ddot{B}\ddot{C}}{BC} = -p_\wedge, \tag{6}$$

$$\frac{\ddot{C}}{C} + \frac{\ddot{A}}{A} + \frac{\dot{C}\dot{A}}{CA} = -p_\wedge, \tag{7}$$

where over dot ($\cdot$) represents derivative with respect to time *t*. The volume scale factor *V* and average scale factor a are given by

$$V = a^3 = ABC \tag{8}$$

The equations (4) - (7) contains six unknowns $A, B, C, \rho_\wedge, \rho_m, p_\wedge$. Two additional constraints relative to these parameters are required to find the explicit solutions and we assume that the component σ_1^1 of the shear tensor σ_i^j is proportional to the expansion scalar (θ) i.e. $\sigma_1^1 < \theta$ which leads to the relation between the metric potential as

$$A = (BC)^m, \tag{9}$$

where *m* is the positive constant.
Subtracting equation (7) from equation (5), and integrating we obtain

$$\frac{B}{C} = c_1 \exp\left[c_2 \int (ABC)^{-1} dt\right], \tag{10}$$

where c_1 and c_2 are constants of integration.

Solving equations (8), (9) and (10), we obtain the metric functions as

$$A(t) = a^{\frac{3m}{m+1}}, \tag{11}$$

$$B(t) = \sqrt{c_1}\, a^{\frac{3}{2(m+1)}} \exp\left[\frac{c_2}{2}\int \frac{1}{a^3}dt\right], \tag{12}$$

$$C(t) = \frac{1}{\sqrt{c_1}}\, a^{\frac{3}{2(m+1)}} \exp\left[-\frac{c_2}{2}\int \frac{1}{a^3}dt\right]. \tag{13}$$

We assume that both the components do not conserving separately but interacting with each other in such a way that the balance equation takes the form

$$\dot{\rho}_m + \left(\frac{\dot{V}}{V}\right)\rho_m = Q\,, \tag{14}$$

$$\dot{\rho}_\wedge + \left(\frac{\dot{V}}{V}\right)(1+\omega_\wedge) = -Q\,, \tag{15}$$

Where Q>0 measures the strength of interaction and $\omega_\wedge = \frac{p_\wedge}{\rho_\wedge}$ is the equation of state parameter for the holographic dark energy. Wetterich ([71], [72]) (also Billyard and Coley [20]) has introduced models featuring an interaction matter-dark energy and Horvat [34] used alongside the holographic dark energy. Although the assumption of a coupling between both the component simplies the introduction of an additional phenomenological function *Q*, a description that admits interaction is certainly more general than otherwise.A vanishing *Q* implies that the conservation of matter and dark energy. Considering the continuity equations, the interaction between dark matter and dark energy must be the function of energy density multiplied by the quantity with units of inverse of time, which can be chosen as a Hubble factor H . A freedom has been given to choose the form of energy density, which may be any combination of dark matter and dark energy. Thus, phenomenologicallyin the form such as (Guo *et al*. [30], [32]; Amendola *et al*. [8]) the interaction between dark matter and dark energy can be express as

$$Q = 3b^2 H\rho_m = b^2\frac{\dot{V}}{V}\rho_m\,, \tag{16}$$

where b^2 is coupling constant.

The energy density of dark matter is obtained from equations (11) and (13) as

$$\rho_m = \rho_0 V^{(b^2-1)}\,, \tag{17}$$

where $\rho_0 > 0$ is the real constant of integration.

From equations (16) and (17) ,we obtained the interacting term as

$$Q = 3\rho_0 b^2 H V^{(b^2-1)} \tag{18}$$

Cosmological solution for variable deceleration parameter

We consider the deceleration parameter to be a variable

$$q = -\frac{a\ddot{a}}{\dot{a}^2} = -\frac{\ddot{a}}{aH^2} = b(t) \text{ variable.} \tag{19}$$

and following Pradhan *et al*. [48]also used by Chawla C. *et al*. [23],we assume the law of variation of scale factor as increasing function of time

$$a(t) = \left[\sinh(\alpha t)\right]^{\frac{1}{n}}\quad . \tag{20}$$

Using (2) in equations (11) - (13), we obtain the expressions for scale factors as

$$A(t) = \left[\sinh(\alpha t)\right]^{\frac{3m}{n(m+1)}}\,, \tag{21}$$

$$B(t) = \sqrt{c_1}\left[\sinh(\alpha t)\right]^{\frac{3m}{2n(m+1)}}\exp\left[\frac{c_2}{2}\int\frac{1}{\left[\sinh(\alpha t\right]^{\frac{3}{n}}}\right], \tag{22}$$

$$C(t) = \frac{1}{\sqrt{c_1}}\left[\sinh(\alpha t)\right]^{\frac{3m}{2n(m+1)}}\exp\left[-\frac{c_2}{2}\int\frac{1}{\left[\sinh(\alpha t\right]^{\frac{3}{n}}}\right]. \tag{23}$$

Using equations (8) and (20) in equation (17) & (16), we get

$$\rho_m = \rho_0\left[\sinh(\alpha t)\,\right]^{\frac{3}{n}(b^2-1)}\,, \tag{24}$$

$$Q = \frac{3}{n}\rho_0 b^2\alpha\coth(\alpha t)\left[\sinh(\alpha t)\right]^{\frac{3}{n}(b^2-1)} \tag{25}$$

Using equations (20)-(23) and (24) in equation (4), we obtain the energy density of holographic dark energy as

$$\rho_\wedge = \frac{9}{4}\frac{\alpha^2(4m+1)}{n^2(m+1)^2}Coth^2(\alpha t) - \rho_0\left[\sinh(\alpha t)\right]^{\frac{3}{b}(b^2-1)} - \left(\frac{c_2}{2\left[\sinh(\alpha t)\right]^{\frac{3}{n}}}\right)^2. \tag{26}$$

Using equations (21)-(23) in equation (5), we obtain the pressure of holographic dark energy as,

$$p_\wedge = \frac{3}{2}\frac{\alpha^2(2m+1)}{n(m+1)}\operatorname{cosech}^2(\alpha t) - \frac{9\alpha^2(4m^2+2m+1)}{4n^2(m+1)^2}\coth^2(\alpha t) - \left(\frac{c_2}{2\left[\sinh(\alpha t)\right]^{\frac{3}{n}}}\right)^2. \tag{27}$$

The EoSparameter of holographic dark energy is given by

$$\omega_\wedge = \frac{6n(m+1)(2m+1)\operatorname{cosech}^2(\alpha t) - 9(4m^2+2m+1)\coth^2(\alpha t) - \left[\frac{c_2 n(m+1)}{\alpha(\sinh(\alpha t))^{\frac{3}{n}}}\right]^2}{9(4m+1)\coth^2 - 4\rho_0 n^2(m+1)^2(\sinh(\alpha t))^{\frac{3}{n}(b^2-1)} - \left[\frac{c_2 n(m+1)}{\alpha(\sinh(\alpha t))^{\frac{3}{n}}}\right]^2}. \tag{28}$$

Using equations (19) and (20) time varying deceleration parameter is obtained as

$$q = n\left[1-\tanh^2(\alpha t)\right] - 1\,. \tag{29}$$

The physical parameters such as spatial volume *V*, Hubble parameter *H*, expansion scalar θ, shear scalar σ and mean anisotropy parameter Δ are given by

$$V = \left[\sinh(\alpha t)\right]^{\frac{3}{n}}\,, \tag{30}$$

$$H = \frac{\alpha}{n}\coth(\alpha t)\,, \tag{31}$$

$$\theta = 3H = \frac{3\alpha}{n}\coth(\alpha t)\,, \tag{32}$$

$$\sigma^2 = 3\left[\frac{\alpha(2m-1)}{2n(m+1)}\coth(\alpha t)\right]^2 + \left[\frac{c_2}{2(\sinh(\alpha t))^{\frac{3}{n}}}\right]^2, \tag{33}$$

$$\Delta = \frac{1}{2}\left[\frac{(2m-1)}{(m+1)}\right]^2 + \frac{1}{6}\left[\frac{c_2 n}{\alpha \coth(\alpha t)\left[\sinh(\alpha t)\right]^{\frac{3}{n}}}\right]^2 \quad (34)$$

CONCLUDING REMARK

The present work involves spatial homogeneous and anisotropic Bianchi Type-I universe field with dark matter and holographic dark energy. We have obtained the cosmological solution from the field equations by considering the variable deceleration parameter.

The main feature of the work is as follows.

1. The sign of q represents that the universe is decelerating or accelerating i.e. a positive sign of q represents accelerating universe and negative sign of q represents decelerating universe.
   In our model $q > 0$ for $t \to 0$ and $q \leq -1$ for $t \to \infty$ i.e. the model represents the decelerating to accelerating phase and the values of deceleration parameter lies in the phase $-1 \leq q < 0$ ([6], [23], [26])
2. From the equation (30), the spatial volume $V \to 0$ as $t \to 0$ and $V \to \infty$ for $t \to \infty$, which indicates that the universe starts with zero volume and expands as cosmic time t increases.
3. From the equation (31), the Hubble parameter H diverges at $t \to 0$ and converges at $t \to \infty$.
4. From the equation (34), we can say that the anisotropic parameter of expansion dies out very quickly after inflation.
5. From the equation (27), we observe that $p_\wedge$ (pressure of dark energy) tends to negative value at late lime, which indicates that the universe is accelerating from SNe Ia observation.
6. From the equation (3.10), we observed that $\omega < -1$ for large cosmic time. The EoS parameter found to be negative $\omega_\wedge < -1$ (i.e. the phantom region) ([55], [56], [13]).
7. It is also observed that pressure of dark energy, density of dark energy, Hubble parameter, expansion scalar, shear scalar are diverges and the spatial volume directional scale factors vanishes at $t = 0$, hence the model has point type singularity [39].

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