ISSN: 0976-3031

Available Online at http://www.recentscientific.com

CODEN: IJRSFP (USA)

International Journal of Recent Scientific Research
Vol. 8, Issue, 7, pp. 18471-18476, July, 2017

International Journal of Recent Scientific Research

DOI: 10.24327/IJRSR

Research Article

BIANCHI TYPE-VI*h* UNIVERSE FILED WITH INTERACTING COLD DARK MATTER AND HOLOGRAPHIC DARK ENERGY

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DOI: http://dx.doi.org/10.24327/ijrsr.2017.0807.0515

ARTICLE INFO

Article History:

Received 15th April, 2017
Received in revised form 25th May, 2017
Accepted 23rd June, 2017
Published online 28th July, 2017

Key Words:

Bianchi type-VI$_h$, space-time, Interacting dark fluids, Statefinder Parameters.

ABSTRACT

In the present work, we have solved Einstein field equations in presence of Holographic dark energy and interacting Dark matter in space-time describe by spatially homogeneous and anisotropic Bianchi type-VI$_h$. The solution of field equations are obtained under the condition of the expansion scalar (θ) is proportional to shear scalar (σ). In order to distinguish between our dark energy model with other existing dark energy models, the State finder diagnostic is applied to the model. The physical and kinematical properties of the models are also discussed.

INTRODUCTION

Recently physicists and astronomers through their cosmological observational data discovered that the universe is undergoing the state of accelerated expansion at present time by Type Ia supernovae (SNeIa) (Riess *et al.* 1998; Perlmutter *et al.* 1999). The universe is spatially flat and dominated by exotic component with large negative pressure called 'dark energy', this observational data have been suggested by cosmic microwave background (CMB) (Bennett *et al.* 2003; Spergel *et al.* 2003) and large -scale structure (LSS) (Tegmark *et al.*2004a; Tegmark *et al.* 2004b). Our universe consists of 73% Dark Energy (DE) that causes cosmic acceleration, 23% dark matter (DM) and 4% ordinary matter (baryonic matter). This result was indicated byWilkinson Microwave Anisotropy Probe (WMAP) (Peebles and Ratra 2003; Padmanabhan 2003; Weinberg 1989; Carroll 2001). The most crucial problem in modern cosmology is to understand the acceleration of cosmic expansion. Transformation of earlier deceleration to present acceleration occurs due to exotic type of unknown force with positive energy density with negative pressure, called as dark energy. To solve the problem of dark energy, many activities is going on theoretical and observational sector of physics community. For explaining cosmic acceleration cosmological constant (Λ) is used, which is the most simplest and natural candidate for dark energy with equation of state $w_\Lambda = -1$ (Nojiri and Odinstov 2003).

Dynamical dark energy model like cosmological constant or vacuum energy (Weinberg 1989), quintessence scalar field models (Wetterich 1988; Ratra and Peeble 1988), k-essence (Chiba *et al.* 2000; Armendariz-picon *et al.* 2000; Armendarizs-Picon *et al.*2001), tachyon field (Sen 2002; Padmanabhan and Chaudhury 2002), Chaplygin gas (Kamenshchik *et al.* 2001; Bento *et al.* 2002), quintom (Elizalde *et al.* 2004; Anisimov *et al.*2005), phantom (Caldwell 2002) have been investigated the properties of dark energy. Different dark energy cosmologies (isotropic) with early deceleration and late time acceleration have been recently reviewed by Bamba *et al.* (2012). The accelerating expansion with quintessence/phantom nature in detail along with cosmography test has been represented by cosmological models like Holographic dark energy, coupled dark energy, f(R) gravity, f(R,T) gravity, f(T) gravity, Scalar field theory. These models have been studied by Bamba *et al.* (2012). Reddy *et al.* (2012) have investigated five dimensional dark energy models in a scalar tensor theory of gravitation. Ram *et al.* (2016) have investigated Kantowshi-Sachs cosmological model in the presence of an anisotropic dark energy within the frame work of Lyra geometry.

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The simplest and reasonable frame to investigate the problem of dark energy is provided by holographic dark energy models (HDE). Holographic dark energy is a component of dark energy, which is based on a holographic principle. Holographic principle provides another way to find the solution of dark energy problem. Firstly, Hooft (1999) put forward holographic principle in the context of black hole physics. New version of holographic principle has been proposed by many authors (Fisher Sussikind 1998; Cohen *et al.* 1999; Horava and Minic 2000; Li 2004). This principle states that the number of degree of freedom related directly to entropy scale with enclosing the area of system.

In many literatures, work has been done, which is related with holographic dark energy. The holographic density of the form $\rho_\Lambda \approx \alpha_0 H^2 + \beta_0 \dot{H}$, where H is the Hubble parameter and α_0, β_0 are constants was proposed by Granda and Oliveros (2008), which fulfill the restriction enforced by current observational data. They have noted out that current observational data consistence with this new model of dark energy and accelerating expansion of the universe was represented by this model. Granda and Oliveros (2009) have investigated the interaction between this holographic dark energy model in Flat Freidman-Robertson-Walker (FRW) universe with various dark energy models like tachyon, quintessence, and k-essence.

Various astronomical observations tested and constrained holographic DE model (Zhang and Wu 2005; Enqvist, Hannestad and Sloth 2005; Shen, Wang, Abdalla and Su 2005; Chang, Wu and Zhang 2006; Sadjadi 2007; Guo, Ohta and Zhang 2005, 2007). Many researchers studied the interaction between holographic dark energy and dark matter (Carvalho and Saa 2004; Pavon and Zimdahl 2005; Wang *et al.*2005). The interaction between holographic dark energy with one of them (tachyon, phantom, chaplygin gas) in FRW universe has been studied by many researchers (Setare 2007; Banerjee and Pavon 2007; Kim *et al.* 2006; Zimdahl and Pavon 2007; Zimdahl 2008).

Recently, Reddy *et al.* (2016) have studied Bianchi type-VI$_0$ universe filled with matter and holographic dark energy in scalar tensor theory by using hybrid law. Also, Reddy *et al.* (2016) have investigated Bianchi type universe filled with matter and holographic dark energy component in scalar tensor theory using condition that scalar expansion is proportional to the shear scalar and linearly varying deceleration parameter. Sarkar (2014a, 2014b, 2014c) have studied holographic dark energy model in Bianchi space-time with linearly varying deceleration parameter in general relativity. Also, Sarkar and Mahanta (2013a, 2013b) discussed minimally interacting holographic dark energy model in Bianchi space-time with constant deceleration parameter. Adhav (2014, 2015) have investigated Interacting dark matter and Holographic dark energy in Bianchi type I and V by using (i) special form of deceleration parameter and (ii) applying the special law of variation of Hubble parameter that gives constant value of deceleration parameter. Besides some interacting models are discussed in many works because these models can help to understand or assuage the coincidence problem by considering the possible interaction between dark energy and cold dark matter due to the unknown nature of dark energy and dark matter. In addition, the proposal of interacting dark energy is compatible with the current observations such as the CMB and SNIa data (Guo, Ohta and S. Tsujikawa 2007).

In this paper, we have studied the interacting cold dark matter and holographic dark energy in Bianchi type-VI$_h$ space-time in theory of gravitation. The structure of this paper is as follows: In section 2, we derive the Einstein field equation with the help of Bianchi type-VI$_h$ metric in presence of interacting cold dark matter and holographic dark energy component. Section 3 deals with the cosmological solution of field equation obtained by using condition that the expansion scalar (θ) is proportional to shear scalar (σ). Physical and geometrical aspect are studied and discussed in section 4 and 5. The last section 6 is the conclusion.

Metric and Field Equations

The Bianchi Type-VI$_h$ line element can be written as (Mishra and Sahoo 2014)

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

where A and B are the scale factors and functions of time t only.

The Einstein's field equations are ($8\pi G = 1$ and $c = 1$)

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

where ${}^{m}T_{ij} = \rho_m u_i u_j$ and ${}^{\Lambda}T_{ij} = (\rho_\Lambda + p_\Lambda) u_i u_j + g_{ij} p_\Lambda$. (3)

${}^{\Lambda}T_{ij}$ and ${}^{m}T_{ij}$ are matter tensors for holographic dark energy and cold dark matter (pressure-less i.e. $w_m = 0$). Here ρ_Λ and p_Λ are the energy density and pressure of holographic dark energy and ρ_m is the energy density of dark matter.

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

$$\frac{\ddot{B}}{B} + \frac{\ddot{C}}{C} + \frac{\dot{B}\dot{C}}{BC} - \frac{h}{A^2} = -p_\Lambda \,, \tag{4}$$

$$\frac{\ddot{A}}{A} + \frac{\ddot{C}}{C} + \frac{\dot{A}\dot{C}}{AC} - \frac{h^2}{A^2} = -p_\Lambda \,, \tag{5}$$

$$\frac{\ddot{A}}{A} + \frac{\ddot{B}}{B} + \frac{\dot{A}\dot{B}}{AB} - \frac{1}{A^2} = -p_\Lambda \,, \tag{6}$$

$$\frac{\dot{B}\dot{C}}{BC} + \frac{\dot{A}\dot{C}}{AC} + \frac{\dot{A}\dot{B}}{AB} - \frac{1+h+h^2}{A^2} = \rho_\Lambda + \rho_m \,, \tag{7}$$

$$\frac{2\dot{A}}{A} - \frac{\dot{B}}{B} - \frac{\dot{C}}{C} = 0 \,, \tag{8}$$

where the overhead dot (**.**) represents derivative with respect to cosmic time *t*.

Here we discuss particular case for $h=1$. Then Einstein field equation can be written as

$$\frac{\ddot{B}}{B}+\frac{\ddot{C}}{C}+\frac{\dot{B}\dot{C}}{BC}-\frac{1}{A^2}=-p_\Lambda\ , \tag{9}$$

$$\frac{\ddot{A}}{A}+\frac{\ddot{C}}{C}+\frac{\dot{A}\dot{C}}{AC}-\frac{1}{A^2}=-p_\Lambda\ , \tag{10}$$

$$\frac{\ddot{A}}{A}+\frac{\ddot{B}}{B}+\frac{\dot{A}\dot{B}}{AB}-\frac{1}{A^2}=-p_\Lambda\ , \tag{11}$$

$$\frac{\dot{B}\dot{C}}{BC}+\frac{\dot{A}\dot{C}}{AC}+\frac{\dot{A}\dot{B}}{AB}-\frac{3}{A^2}=\rho_\Lambda+\rho_m\ , \tag{12}$$

$$\frac{2\dot{A}}{A}-\frac{\dot{B}}{B}-\frac{\dot{C}}{C}=0\ . \tag{13}$$

Equation (13) gives,

$A^2=k(BC)$, where k is a constant of integration.

The Einstein field equations (9)-(12) using equation (13) reduces to,

$$\frac{2\ddot{A}}{A}+\frac{2\dot{A}\dot{B}}{AB}+\frac{\dot{B}^2}{B^2}-\frac{1}{A^2}=-p_\Lambda\ , \tag{14}$$

$$\frac{3\ddot{A}}{A}-\frac{\ddot{B}}{B}+\frac{2\dot{A}^2}{A^2}-\frac{\dot{A}\dot{B}}{AB}-\frac{1}{A^2}=-p_\Lambda\ , \tag{15}$$

$$\frac{\ddot{A}}{A}+\frac{\ddot{B}}{B}+\frac{\dot{A}\dot{B}}{AB}-\frac{1}{A^2}=-p_\Lambda\ , \tag{16}$$

$$\frac{2\dot{A}^2}{A^2}-\frac{\dot{B}^2}{B^2}+\frac{2\dot{A}\dot{B}}{AB}-\frac{3}{A^2}=\rho_\Lambda+\rho_m\ . \tag{17}$$

Here, we considered that both components i.e. cold dark matter and holographic dark energy interact with each other but do not conserve separately in such a manner that the balance equations can be written as

$$\dot{\rho}_m+\left(\frac{\dot{V}}{V}\right)\rho_m=Q\ , \tag{18}$$

$$\dot{\rho}_\Lambda+\left(\frac{\dot{V}}{V}\right)(1+w_\Lambda)\rho_\Lambda=-Q\ , \tag{19}$$

where the equation of State parameter for holographic dark energy is given by $w_\Lambda=\frac{p_\Lambda}{\rho_\Lambda}$ and the strength of the interaction is measured by $Q>0$. Wetterich (1988, 1995) introduced Models featuring an interaction matter-dark energy and Horvat (2004) used firstly this model alongside the holographic dark energy. The assumption of coupling between both components i.e. dark matter and dark energy gives introduction to additional phenomenological function *Q*. Interaction and arguments in favour of interacting models have been estimated recently, this would not be expressed by any known symmetry (Farrar and Peebles 2004). Dark energy and matter remain separately conserved; this is implied by a vanishing *Q*. According to continuity equations, the interaction between DE and DM express as a function of energy density multiplied by a quantity with units of inverse of time, which can be chosen as the Hubble factor *H*. Any combination of DE and DM can be chosen to form energy density. Cai and Wang (2005), Guo *et al*. (2007) and Amendola *et al*. (2007) expressed the interaction DE and DM phenomenological in forms such as

$$Q=3b^2H\rho_m=b^2\frac{\dot{V}}{V}\rho_m\ , \tag{20}$$

where b^2 is a coupling constant. In order to avoid the coincidence problem same relation for interacting phantom dark energy and dark matter have been taken by Cai and Wang (2005).

From equations (18) and (20), the energy density of dark matter is given as

$$\rho_m=\rho_0V^{(b^2-1)}\ , \tag{21}$$

where $\rho_0>0$ is a real integrating constant.

From equations (20) and (21), we get the interacting term *Q* as

$$Q=3\rho_0b^2HV^{(b^2-1)}\ . \tag{22}$$

Cosmological Solutions

In order to find solutions of the Einstein field equations, we consider that the expansion scalar (θ) is proportional to the shear scalar (σ). This condition leads to

$$A=B^m\ , \tag{23}$$

where $m>1$ is constant.

Subtracting equation (14) from equation (15), we get

$$\frac{\ddot{B}}{B}-\frac{\ddot{A}}{A}+\frac{3\dot{A}\dot{B}}{AB}-\frac{2\dot{A}^2}{A^2}-\frac{\dot{B}^2}{B^2}=0\ . \tag{24}$$

Using equation (23) in the equation (24) and then on integrating, we get the value of scale factors as

$$A=[3m(k_1t+k_2)]^{1/3}\ , \tag{25}$$

$$B=[3m(k_1t+k_2)]^{1/3m} \tag{26}$$

$$C=\frac{1}{k}[3m(k_1t+k_2)]^{(2m-1)/3m}\ , \tag{27}$$

where $k_1>0$ and k_2 are real constants of integration.

The volume scale factor *V* is defined and obtained as

$$V=ABC=\frac{1}{k}[3m(k_1t+k_2)]\ . \tag{28}$$

Using equations (25-27), we get the mean Hubble parameter and mean anisotropy (H), parameter of expansion (Δ) obtained as,

$$H = \frac{\dot{a}}{a} = \frac{1}{3}\frac{\dot{V}}{V} = \frac{k_1}{3(k_1 t + k_2)}, \tag{29}$$

$$\Delta = \frac{1}{3}\sum_{i=1}^{3}\left(\frac{H_i - H}{H}\right)^2 = \frac{(m-1)^2}{m^2} + \frac{(m+1)^2}{(2m-1)^2}, \tag{30}$$

where $a = V^{1/3}$ is the mean scale factor and $H_1 = \frac{\dot{A}}{A}$, $H_2 = \frac{\dot{B}}{B}$, $H_3 = \frac{\dot{C}}{C}$ are the directional Hubble parameters in the directions of x, y, z axes respectively.

With the help of equation (28) in equations (21) and (22), we obtain energy density of DM and interaction as

$$\rho_m = \rho_0\{\frac{3m}{k}(k_1 t + k_2)\}^{(b^2-1)}, \tag{31}$$

$$Q = b^2 k_1 \rho_0 (\frac{3m}{k})^{(b^2-1)}(k_1 t + k_2)^{(b^2-2)}. \tag{32}$$

Using equations (25-26) and (31) in the equation (17), we obtain the energy density of holographic dark energy as

$$\rho_\Lambda = \frac{k_1^2(2m^2+2m-1)}{9m^2(k_1 t + k_2)^2} - \frac{3}{[3m(k_1 t + k_2)]^{2/3}} - \rho_0\{\frac{3m}{k}(k_1 t + k_2)\}^{(b^2-1)} \tag{33}$$

Using equations (25), (26) in the linear combination of equations (14-16), we obtain the pressure of holographic dark energy as,

$$p_\Lambda = \frac{k_1^2(2m^2+2m-1)}{9m^2(k_1 t + k_2)^2} + \frac{1}{[3m(k_1 t + k_2)]^{2/3}}. \tag{34}$$

The equation of state (EoS) parameter of holographic dark energy is given by,

$$w_\Lambda = \frac{p_\Lambda}{\rho_\Lambda} = \frac{\frac{k_1^2(2m^2+2m-1)}{9m^2(k_1 t + k_2)^2} + \frac{1}{[3m(k_1 t + k_2)]^{2/3}}}{\frac{k_1^2(2m^2+2m-1)}{9m^2(k_1 t + k_2)^2} - \frac{3}{[3m(k_1 t + k_2)]^{2/3}} - \rho_0\{\frac{3m}{k}(k_1 t + k_2)\}^{(b^2-1)}}. \tag{35}$$

The ratio of dark matter energy density to the dark energy density is called the coincidence parameter and is given by

$$\bar{r} = \rho_m / \rho_\Lambda$$

$$\bar{r} = \frac{\rho_0\{3m(k_1 t + k_2)\}^{(b^2-1)}}{\frac{k_1^2(2m^2+2m-1)}{9m^2(k_1 t + k_2)^2} - \frac{3}{[3m(k_1 t + k_2)]^{2/3}} - \rho_0\{\frac{3m}{k}(k_1 t + k_2)\}^{(b^2-1)}}. \tag{36}$$

Statefinder Diagnostic

Cosmic acceleration is explained by various models. To differentiate between different forms of dark energy in independent manners, Sahni *et al*. (2003) and Alam *et al*.(2003) put forward cosmological diagnostic pair {r, s}defined as 'statefinder parameter', as follows and

$r = \frac{\dddot{a}}{aH^3}$ and $s = \frac{r-1}{3(q-1/2)}$, where q is a deceleration parameter, a denotes scale factor. The statefinder depends on a scale factor 'a' and it is geometrical diagnostic. Since different evolution trajectories in the s-r plane are exhibited by different cosmological models involving dark energy. To differentiate these wide variety of dark energy models including cosmological constant, quintessence, phantom, quintom, chaplygin gas, holographic model; statefinder diagnostic is used (Gorini *et al*. 2003; Zhang 2005; Wu and Yu 2005; Guo, Ohta and S. Tsujikawa2007; Amendola *et al*. 2007;Cai and Wang 2005).

These statefinder parameter characterized the properties of dark energy models and useful to obtained distance of given dark energy model from Λ CDM limit. The statefinder parameter corresponds to a fixed point $\{r = 1, s = 0\}$ indicate Λ CDM scenario and $\{r = 1, s = 1\}$ shows CDM limit (Guo *et al*. 2007).

$r = 10$ and $s = \frac{r}{5}$.

DISCUSSION AND CONCLUSION

In this paper, we have discussed the anisotropic and homogeneous Bianchi type-VI_h universe filled with interacting Dark matter and Holographic dark energy and studied the statesfinder parameters of the holographic dark energy models. The solutions of the field equations are obtained under the assumption of expansion scalar (θ) is proportional to shear scalar (σ). It was argued that an equation of state of dark energy $w_\Lambda < 0$ is necessarily accompanied by the decay of the dark energy component into pressure-less dark matter ($b^2 > 0$). In our model as $t \to 0, v \to cons\tan t$ and as $t \to \infty, v \to \infty$ and hence there is no Big-Bang type of initial singularity and universe expand as time increases.

As $t \to 0, \omega_\Lambda \to \infty$, and as time increases ω_Λ emerges from phantom region and after some finite time, it reaches to $\omega_\Lambda = -1$ (cosmological constant),which represent the Λ CDM model. After some finite time then it approaches to quintessence region $(-1 < \omega < -1/3)$. The available observational data in cosmology, especially the SDSS data (Eisenstein *et al*. 2005), the SNeIa data (Riess *et al*.2004; Astier *et al*.2006), and the three year WMAP data (Spergel *et al*.2003) all indicate that the $\wedge$CDM model or the model that reduces to $\wedge$CDM are serves as a standard model in cosmology and which resemble with present universe. In order to differentiate between our dark energy models with other existing dark energy models, the Statefinders diagnostic is applied to our model. The Fig. 2 shows the evolving trajectory in the *s-r* plane for the corresponding models is quite different from those of other DE models. Also for any choice of constants, we cannot avoid the coincident problem in our model.

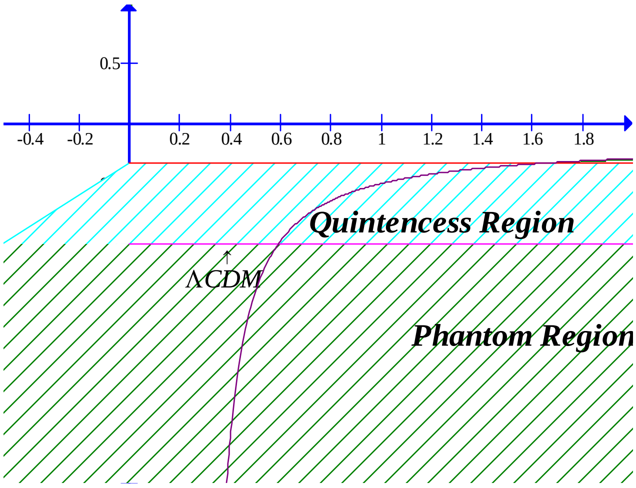

Fig 1 Evolution of EoS parameter (w_Λ).

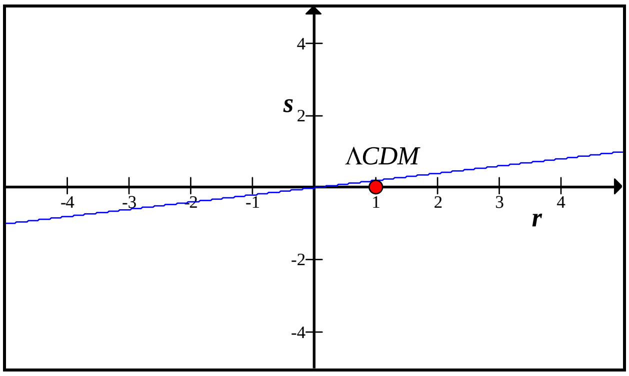

Fig 2 Statefinder parameters s v/s r.

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How to cite this article:

Mete V.G *et al*.2017, Bianchi Type-Vih Universe Filed With Interacting Cold Dark Matter And Holographic Dark Energy. *Int J Recent Sci Res*. 8(7), pp. 18471-18476. DOI: http://dx.doi.org/10.24327/ijrsr.2017.0807.0515

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