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Research Article

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Magnetized dark energy cosmological models with constant deceleration parameter

Abstract

In this paper we investigated Homogenous - Hyper surface magnetized dark energy models with constant deceleration parameter. The energy-momentum tensor consists of anisotropic fluid with anisotropic EoS $p=\omega\rho$ and a uniform magnetic field of energy density ρ_B. We have obtained exact solutions to the field equations using the condition that scalar expansion is proportional to the shear scalar. The physical behaviors of the models are discussed with and without magnetic field. We conclude that universe model as well as anisotropic fluid does not approach isotropy through the evolution of the universe. The physical aspects of the dark energy models are also discussed.

Keywords: Hyper surface Universe; Dark energy; EoS parameter

Volume 1 Issue 4 - 2017

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Received: September 11, 2017 | **Published:** October 13, 2017

Introduction

The discovery of accelerated expansion of the universe[1,2] led to a number of new ideas in cosmology. Recent observations of supernovae are consistent with the universe made up 71.3% of dark energy and only 27.4% of a combination of dark matter and baryonic matters.[3] Dark Energy (DE) has been conventionally characterized by the equation of state (EoS) parameter $\omega=\frac{p}{\rho}$ which is not necessarily constant. SNIa data collaborated with CMBR anisotropy and galaxy clustering statistics suggest that $-1.33<\omega<-0.79$ [4] Due to lack observational evidence in making a distinction between constant and variable ω, usually the equation of state parameter is considered as a constant[5,6] with phase wise value -1, 0, $\frac{-1}{3}$ and $+1$ for vacuum fluid, dust fluid, radiation and stiff dominated universe, respectively. New dark energy models in anisotropic Bianchi type-I (B-I) space-time with variable EoS parameter and constant deceleration parameter have been investigated by Pradhan et al.[7] The Bianchi type III dark energy models with constant deceleration parameter are investigated by Yadav et al.[8] Locally rotationally symmetric (LRS) Bianchi Type I cosmological models are examined by Akarsu et al.[9] in the presence of dynamically anisotropic dark energy and perfect fluid. They assume that the DE is minimally interacting, has dynamical energy density, anisotropic EoS parameter. Some new exact solutions of Einstein's field equations emerged in a spatially homogeneous and anisotropic Bianchi type-V space-time with minimally interacting perfect fluid and anisotropic DE components, which has dynamic EoS parameter investigated by Pradhan et al.[10] A special law of variation for Hubble's parameter is presented by S Kumar et al.[11] in a spatially homogeneous and anisotropic Bianchi type-I space-time that yields a constant value of deceleration parameter.A spatially homogeneous and anisotropic but LRS Bianchi type-II cosmological model is studied by CP Kumar et al.[12] with a perfect fluid and constant deceleration parameter. Akarsu et al.[13,14] have investigated Bianchi-I and Bianchi-III DE models with constant Deceleration Parameter. Yadav et al.[15] studied spatially homogeneous and anisotropic locally rotationally symmetric (LRS) Bianchi-I cosmological model in the presence of magnetized dark energy. Sahoo et al.[16] investigated axially-symmetric cosmological model with anisotropic DE. Recently, Katore et al.[17] studied magnetized anisotropic DE models for Bianchi type-V space–time with constant deceleration parameter. Very recently, Shaikh et al.[18] have studied plane-symmetric Universe with variable ω in the presence and the absence of magnetic field of energy density ρ_B together with constant deceleration parameter.

Motivated by above research work, in this paper, we have investigated the magnetized anisotropic DE models with variable ω. This paper is organized as follows: In Section 2, the metric and field equations are described. The solution of field equations are presented in Section 3. Section 4 deals with cases for $s \neq 0 \;\&\; s = 0$ and section 5 concludes the findings.

Metric and Field Equations

General solutions of Einstein's field equations for a perfect fluid satisfying a barotropic equation of state have been obtained by Stewart et al.[19]. Hajj-Boutros[20] developed a method to build exact solutions of field equations in case of the following metric in presence of perfect fluid and obtained exact solutions of the field equations which add to the rare solutions not satisfying the barotropic equation of state. Some hyper surface-homogeneous bulk viscous fluid cosmological models with time-dependent cosmological term have been studied by Verma et al.[21]

The general metric for a hyper surface Homogenous space time can be described by

$$ds^2=-dt^2+A^2(t)\,dx^2+B^2(t)\left[dy^2+\Sigma^2(y,K)\,dz^2\right] \tag{2.1}$$

Where A, B are functions of t only and $\Sigma(y,K)=\sin y, y, \sinh y$ respectively when $k=1,-1,0$.

Katore et al.[22] obtained the exact solutions of the field equations for Hyper surface-homogeneous space time under the assumption on the anisotropy of the fluid (dark energy), which are obtained for exponential and power-law volumetric expansions in a scalar-tensor theory of gravitation. Katore et al.[23] presented a class of solutions of Einstein's field equations describing two-fluid models of the universe in Hyper surface-Homogenous space time. Shaikh et al.[24] proposed the study of cosmological model represented by hyper surface -Homogenous reference system for perfect fluid distribution within the framework of $f(R,T)$ gravity.

The Einstein field equations, in gravitational units ($c=1$ and $8\pi G=1$) are

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

Where R_{ij} is the Ricci tensor, R is the Ricci scalar, and T_{ij} is the energy-momentum tensor for magnetized anisotropic fluid.

Now we consider more general energy-momentum tensor for magnetized anisotropic dark fluid in the following form

$$T_i^j=dig\left[-\rho-\rho_B, p_x+\rho_B, p_y-\rho_B, p_z-\rho_B\right] \tag{2.3}$$

Where ρ is the energy density of the fluid; p_x , p_y and p_z are pressures on *x, y* and *z* axes respectively and ρ_B stands for energy density of magnetic field. The anisotropic fluid is characterized by the EoS $p=\omega\rho$, where ω is not necessarily constant.[25]

From Equation (2.3), we have

$$T_i^j=dig\left[-\rho-\rho_B, \omega\rho+\rho_B, (\omega+\gamma)\rho-\rho_B, (\omega+\gamma)\rho-\rho_B\right] \tag{2.4}$$

Where $\omega_x=\omega\rho+\rho_B$, $\omega_y=\omega+\gamma$ and $\omega_z=\omega+\gamma$ are the directional EoS parameters on *x, y* and *z* axes respectively. γ is the deviation free EoS parameter on *y* axis and *z* axis.

Jacobs[26] studied the impact of a regular, early magnetic flux on Bianchi type-I cosmological model. To discuss the effects of magnetic flux on the evolution of the Universe, King et al.[27] used the magnetic perfect fluid energy–momentum tensor. Bianchi type-I cosmological model in the presence of magnetic anisotropic dark energy is obtained by Sharif et al.[28]. Katore et al.[29] investigated Bianchi type-III cosmological model in the presence of magnetic anisotropic dark energy. Zeldovich et al.[30] underlined the importance of magnetic field for a variety of astrophysical phenomena.

In a commoving coordinate system, for the anisotropic hyper surface Homogenous metric (2.1), Einstein field equations (2.2) together with Equation (2.4) lead to the following system of equations

$$2\frac{\dot{A}\dot{B}}{AB}+\frac{\dot{B}^2}{B^2}+\frac{K}{B^2}=\rho+\rho_B \tag{2.5}$$

$$2\frac{\ddot{B}}{B}+\frac{\dot{B}^2}{B^2}+\frac{K}{B^2}=-\omega\rho-\rho_B \tag{2.6}$$

$$\frac{\ddot{A}}{A}+\frac{\ddot{B}}{B}+\frac{\dot{A}\dot{B}}{AB}=-(\omega+\gamma)\rho+\rho_B \tag{2.7}$$

The energy conservation equation related to cosmic fluid and magnetic field is given by

$$\dot{\rho}+\left(\frac{\dot{A}}{A}+2\frac{\dot{B}}{B}\right)(1+\omega)\rho+2\frac{\dot{B}}{B}\gamma\rho+\dot{\rho}_B+2\frac{\dot{A}}{A}\rho_B=0 \tag{2.8}$$

Here the overhead dot on A, *B* and elsewhere denote differentiation with respect to *t*.

Solution of field equations

The Field Equations (2.5)-(2.7) are a system of three linearly independent equations with six unknown parameters $(A, B, \rho, \rho_B, \omega, \gamma)$ .Thus system is initially undetermined and we need additional constraints to solve the system.

(i) We constrain the system of equations with a law of variation for the Hubble parameter proposed by Berman[31] for solving FRW models, which yields a constant value of deceleration parameter (DP). Singh et al.[32] have studied flat FRW and Bianchi type models by using the special law of Hubble parameter that yields constant value of deceleration parameter. A similar law of variation for the Hubble parameter in anisotropic space-time metrics that yields a constant value of the deceleration parameter, and generated solutions for Bianchi Type-I,[33] LRS Bianchi Type-II,[11,34] Bianchi Type-V metric in General Relativity have been proposed .

(ii) We assume that the scalar expansion (θ) in the model is proportional to the shear scalar (σ) .

This condition leads to the following relation between the metric potentials:

$$A=B^n \tag{3.1}$$

Where $(n>0)$ is a constant?

The motive behind assuming the constrain is explained with the reference to Thorne [36] observations of velocity red shift relation for extragalactic sources suggest that Hubble expansion of the universe is isotropic about 30% range approximately.[37,38] To put more precisely, redshift studies place the limit $\frac{\sigma}{H}\leq 0.30$. Collins[39] discussed the physical significance of this condition for perfect fluid and barotropic equation of state in a more general case. Roy et al.[40–42] proposed this condition to find exact solution of cosmological models.

The average scale factor *R* of Hyper surface metric is given by

$$R=\left(AB^2\right)^{\frac{1}{3}} \tag{3.2}$$

The generalized mean Hubble parameter *H* is defined as

$$H=\frac{1}{3}\left(H_1+H_2+H_3\right) \tag{3.3}$$

Where $H_1=\frac{\dot{A}}{A}$, $H_2=\frac{\dot{B}}{B}$ and $H_3=\frac{\dot{B}}{B}$ are the directional Hubble parameter *H*, in the direction of *x, y* and *z* axes respectively.

The spatial volume for the model (2.1) is given by

$$V^{\frac{1}{3}}=R^{\frac{1}{3}}=AB^2 \tag{3.4}$$

Using equations (3.2)-(3.4), we obtain

$$H=\frac{1}{3}\frac{\dot{V}}{V}=\frac{\dot{R}}{R}=\frac{1}{3}\left(\frac{\dot{A}}{A}+2\frac{\dot{B}}{B}\right) \tag{3.5}$$

As the line element (2.1) is completely characterized by Hubble parameter *H*. We also use a well-known relation Berman[31] between the average Hubble parameter *H* and average scale factor given as

$$H=k_1R^{-s}, \tag{3.6}$$

Citation: Shaikh AY, Wankhade KS. Magnetized dark energy cosmological models with constant deceleration parameter. *Phys Astron Int J.* 2017;1(4):108–113.
DOI: 10.15406/paij.2017.01.00020

Where $k_1(>0)$ and $s(\geq 0)$ are constants. This is an important relation because it gives the constant value of the deceleration parameter.

We assume that the magnetized dark energy is minimally interacting, hence energy conservation equation (2.8) can be split into two separately additive conserver components: namely, the conservation of energy –momentum tensor for the anisotropic fluid and for the magnetic field.

$$\dot{\rho}+\left(\frac{\dot{A}}{A}+2\frac{\dot{B}}{B}\right)(1+\omega)\rho+2\frac{\dot{B}}{B}\gamma\rho=0\,, \tag{3.7}$$

$$\rho_B=\frac{\alpha}{A^2}\,. \tag{3.8}$$

The deceleration parameter q in cosmology is the measure of the cosmic acceleration of the universe expansion and is defined as

$$q=-\frac{R\ddot{R}}{\dot{R}^2}\,. \tag{3.9}$$

In Berman's law the deceleration parameter can get values $q\geq -1$. For accelerating expansion of the universe, we must have $-1\leq q<0$. It exhibits constant-rate volumetric expansion if $q=0$.

Using Equations (3.5) and (3.6), we have

$$\dot{R}=k_1R^{-s+1}\,, \tag{3.10}$$

$$\ddot{R}=-k_1^2(s-1)R^{-2s+1}\,. \tag{3.11}$$

Using equations (3.9), (3.10), (3.11), we get values for the deceleration parameter for the mean scale factor as:

$$q=s-1 \text{ for } s\neq 0\,, \tag{3.12}$$

$$q=-1 \text{ for } s=0\,. \tag{3.13}$$

The sign of q indicates whether the model accelerates or not. The positive sign of q (i.e. s>1) corresponds to decelerating model whereas the negative sign of q for $0\leq s<1$ indicates acceleration. q=0 for s=1 corresponds to expansion with constant velocity. It is remarkable to mention here that though the current observations of SNe Ia and CMBR favours accelerating models (q<0), but both do not altogether rule out the decelerating ones which are also consistent with these observations.[43]

Using equation (3.10), we obtain the law of average scale factor as

$$R=(Dt+c_1)^{\frac{1}{s}} \text{ for } s\neq 0\,, \tag{3.14}$$

$$R=c_2e^{k_1t} \text{ for } s=0\,, \tag{3.15}$$

Where c_1 and c_2 are constants of integration. Thus, the law (3.6) provides two types of the expansion in the universe i.e., (i) power-law (3.14) and (ii) exponential-law (3.15).

Models for s≠0 and s=0:

Case (i): Model for $s\neq 0$

Using Equations (3.1), (3.5) and (3.12), we get following expression for scale function

$$B(t)=l_0(Dt+c_1)^{\frac{1}{r}}\,, \tag{4.1}$$

$$A(t)=l_1(Dt+c_1)^{\frac{n}{r}}\,, \tag{4.2}$$

Where $l_0=c_3^{\frac{-3}{(n+2)}}$, $r=\frac{s(n+2)}{3}$ and $l_1=l_0^n$.

Therefore, the model (2.1) becomes

$$ds^2=-dt^2+l_1^2(Dt+c_1)^{\frac{2n}{r}}dx^2+l_0^2(Dt+c_1)^{\frac{2}{r}}\left[dy^2+\Sigma^2(y,K)\,dz^2\right]. \tag{4.3}$$

The expression for kinematical parameters the Hubble's parameter H, the scalar expansion, shear scalar, for model (4.3) are given by

$$H=\frac{k_1}{(Dt+c_1)}, \tag{4.4}$$

$$\theta=3H=\frac{3k_1}{(Dt+c_1)}, \tag{4.5}$$

$$\sigma^2=\frac{1}{3}\frac{(n-1)^2D^2}{r^2(Dt+c_1)^2}. \tag{4.6}$$

Using Equations (4.5) and (4.6), we have

$$\frac{\sigma}{\theta}=\frac{D(n-1)}{3\sqrt{3}\,r\,k_1}. \tag{4.7}$$

Using Equations (3.8) and (4.2), we get

$$\rho_B=\frac{\alpha}{l_1^2(Dt+c_1)^2}. \tag{4.8}$$

Using equations (2.5), (3.1), (4.1) and (4.8) we have

$$\rho=\frac{(2n+1)D^2}{r^2(Dt+c_1)^2}+\frac{K}{l_0^2(Dt+c_1)^{\frac{2}{r}}}-\frac{\alpha}{l_1^2(Dt+c_1)^{\frac{2n}{r}}}. \tag{4.9}$$

It is observed that the Hubble parameter H, the scalar expansion, shear scalar, magnetized dark energy density and energy density is the decreasing function of time and approaches 0 as $t\to\infty$. Since

$$\lim_{t\to\infty}\frac{\sigma}{\theta}=constant,$$

The model is not isotropic for large value of t.

We observe that at $t=\frac{-c_1}{D}$, the spatial volume vanishes while all the parameters diverge. Therefore, the model has a big bang singularity at $t=\frac{-c_1}{D}$, which can be shifted to $t=0$ by choosing $c_1=0$.

Using Equations (2.6), (3.1), (4.1), (4.8) and (4.9), the equation of state parameter is given by

$$\omega=\frac{\left[\frac{(2r-3)D^2}{r^2(Dt+c_1)^2}-\frac{K}{l_0^2(Dt+c_1)^{\frac{2}{r}}}-\frac{\alpha}{l_1^2(Dt+c_1)^{\frac{2n}{r}}}\right]}{\left[\frac{(2n+1)D^2}{r^2(Dt+c_1)^2}+\frac{K}{l_0^2(Dt+c_1)^{\frac{2}{r}}}-\frac{\alpha}{l_1^2(Dt+c_1)^{\frac{2n}{r}}}\right]}. \tag{4.10}$$

DOI: 10.15406/paij.2017.01.00020

The SN Ia data suggests that $-1.67<\omega<-0.62$[44] while the limit imposed on ω by a combination of SN Ia data (with CMB anisotropy) and galaxy clustering statistics is $-1.33<\omega<-0.79$.[4] So, if the present work is compared with experimental results mentioned above then, one can conclude that the limit of ω provided by equation (4.10) may accommodated with the acceptable range of EoS parameter.

Using Equations (2.6), (3.1), (4.1), (4.8) and (4.9) and (4.10), the skew ness parameter is given by

$$\gamma=\frac{\left[\frac{\left[(n-1)r-\left(n^2+n-2\right)\right]D^2}{r^2\left(Dt+c_1\right)^2}+\frac{K}{l_0^2\left(Dt+c_1\right)^{\frac{2}{r}}}+\frac{2\alpha}{l_1^2\left(Dt+c_1\right)^{\frac{2n}{r}}}\right]}{\left[\frac{(2n+1)D^2}{r^2\left(Dt+c_1\right)^2}+\frac{K}{l_0^2\left(Dt+c_1\right)^{\frac{2}{r}}}-\frac{\alpha}{l_1^2\left(Dt+c_1\right)^{\frac{2n}{r}}}\right]} \tag{4.11}$$

In absence of magnetic field i.e. $\alpha\to 0$ the value of Hubble's parameter H, the scalar expansion θ, shear scalar σ remains as it is and energy density for magnetic field ,energy density for fluid, the EoS parameter and skew ness parameter given by

$$t\to\infty \tag{4.12}$$

$$\rho=\frac{(2n+1)D^2}{r^2\left(Dt+c_1\right)^2}+\frac{K}{l_0^2\left(Dt+c_1\right)^{\frac{2}{r}}}, \tag{4.13}$$

$$\omega=\frac{\left[\frac{(2r-3)D^2}{r^2\left(Dt+c_1\right)^2}-\frac{K}{l_0^2\left(Dt+c_1\right)^{\frac{2}{r}}}\right]}{\left[\frac{(2n+1)D^2}{r^2\left(Dt+c_1\right)^2}+\frac{K}{l_0^2\left(Dt+c_1\right)^{\frac{2}{r}}}\right]}, \tag{4.14}$$

$$\gamma=\frac{\left[\frac{\left[(n-1)r-\left(n^2+n-2\right)\right]D^2}{r^2\left(Dt+c_1\right)^2}+\frac{K}{l_0^2\left(Dt+c_1\right)^{\frac{2}{r}}}\right]}{\left[\frac{(2n+1)D^2}{r^2\left(Dt+c_1\right)^2}+\frac{K}{l_0^2\left(Dt+c_1\right)^{\frac{2}{r}}}\right]}. \tag{4.15}$$

Case (ii): Model S=0

From Equations (3.1), (3.5) and (3.13) we get following expression for scale function

$$B(t)=L_0\,e^{k_2 t}, \tag{5.1}$$

$$A(t)=L_1\,e^{n k_2 t}, \tag{5.2}$$

Where $L_0=\left(\frac{c_2}{c_4}\right)^{\frac{3}{n+2}}$, $k_2=\frac{3k_1}{n+2}$ and $L_1=L_0^n$.

Therefore, the model (2.1) becomes

$$ds^2=-dt^2+L_1^2\,e^{2nk_2t}dx^2+L_0^2e^{2nk_2t}\left[dy^2+\sum{}^2\left(y,K\right)dz^2\right]. \tag{5.3}$$

The expression for kinematical parameters the Hubble's parameter H, the scalar expansion, shear scalar, for model (5.3) are given by

$$H=\frac{1}{3}(n+2)k_2, \tag{5.4}$$

$$\theta=3H=(n+2)k_2, \tag{5.5}$$

$$\sigma^2=\frac{1}{3}(n-1)^2k_2^2. \tag{5.6}$$

Using Equations (5.5) and (5.6) , we have

$$\frac{\sigma}{\theta}=\frac{1(n-1)}{\sqrt{3}\,(n+2)}. \tag{5.7}$$

Using Equations (3.8) and (5.2), we get

$$\rho_B=\frac{\alpha}{L_1^2\,e^{2nk_2t}}. \tag{5.8}$$

From Equations (2.5), (3.1), (5.1) and (5.8) we have

$$\rho=2nk_2^2+k_2^2+\frac{k}{L_0^2\,e^{2k_2t}}-\frac{\alpha}{L_1^2\,e^{2nk_2t}} \tag{5.9}$$

It is observed that the Hubble parameter H, the scalar expansion, shear scalar, magnetized dark energy density and energy density is the decreasing function of time and approaches 0

As $t\to\infty$. Since $\lim_{t\to\infty}\frac{\sigma}{\theta}=$ constant,

The model is not isotropic for large value of t.

Recent observations of SN Ia[45,46] suggest that the universe is accelerating in its present state of evolution. It is believed that the way universe is accelerating presently; it will expand at the fastest possible rate in future and forever. For $s=0$, we get $q=-1$; incidentally this value of DP leads to $\frac{dH}{dt}=0$, which implies the greatest value of Hubble's parameter and the fastest rate of expansion of the universe. Thus, this model may represent the inflationary era in the early universe and the very late times of the universe.

From Equations (2.6), (3.1), (5.1), (5.8) and (5.9), the equation of state parameter is given by

$$\omega=-\frac{\left[3k_2^2+\frac{k}{L_0^2\,e^{2k_2t}}+\frac{\alpha}{L_1^2\,e^{2nk_2t}}\right]}{\left[(2n+1)k_2^2+\frac{k}{L_0^2\,e^{2k_2t}}-\frac{\alpha}{L_1^2\,e^{2nk_2t}}\right]} \tag{5.10}$$

From Equation (5.10), we observe that $\omega\approx-1$ for sufficiently large time t. Therefore, the late time dynamics of EoS parameter ω represents the vacuum fluid dominated Universe, which is mathematically equivalent to cosmological constant.

Citation: Shaikh AY, Wankhade KS. Magnetized dark energy cosmological models with constant deceleration parameter. *Phys Astron Int J.* 2017;1(4):108–113. DOI: 10.15406/paij.2017.01.00020

From Equations (2.6), (3.1), (5.1), (5.8) and (5.9) and (5.10), the skew ness parameteris given by

$$\gamma=\frac{\left[-\left(n^2+n-2\right)k_2^2+\frac{k}{L_0^2e^{2k_2t}}+\frac{2\alpha}{L_1^2e^{2nk_2t}}\right]}{\left[\left(2n+1\right)k_2^2+\frac{k}{L_0^2e^{2k_2t}}-\frac{\alpha}{L_1^2e^{2nk_2t}}\right]} \quad (5.11)$$

In absence of magnetic field i.e. $\alpha\to 0$ the value of Hubble's parameter H, the scalar expansion θ, shear scalar σ remains as it is and energy density for magnetic field, energy density for fluid , the EoS parameter ω and skewness parameter γ given by

$$s=0 \quad (5.12)$$

$$\rho=\left(2n+1\right)k_2^2+\frac{k}{L_0^2e^{2k_2t}}. \quad (5.13)$$

$$\omega=-\frac{\left[3k_2^2+\frac{k}{L_0^2e^{2k_2t}}\right]}{\left[\left(2n+1\right)k_2^2+\frac{k}{L_0^2e^{2k_2t}}\right]} \quad (5.14)$$

$$\gamma=\frac{\left[-\left(n^2+n-2\right)k_2^2+\frac{k}{L_0^2e^{2k_2t}}\right]}{\left[\left(2n+1\right)k_2^2+\frac{k}{L_0^2e^{2k_2t}}\right]} \quad (5.15)$$

Conclusion

In this paper, we have studied Hypersurface Homogeneous anisotropic DE with variable EoS parameter ω, considering two cases, for $s\neq 0$ and $s=0$ respectively. The special law of variation for Hubble's parameter proposed by Berman[31] yields constant value of Deceleration Parameter given by $q=s-1$, which provides accelerating models of the universe for $s<1$ and decelerating ones for $s>1$. It is observed that in both cases, EoS parameter ω is variable function of time which has been supported by recent observations.[1,2] The EoS parameter of DE evolves within the range predicted by the observations. Since in both cases, $\frac{\sigma}{\theta}=$ constant, the models do not approach isotropy at any time. Therefore, we cannot rule out the possibility of anisotropic nature of DE at least in hyper surface Homogenous framework. It is interesting to note that our investigations resembles to the result obtained by Yadav et al.[15]. The analysis of the models reveals that the present-day universe is dominated by Dark Energy, which can successfully describe the accelerating nature of the universe consistent with the observations.

Acknowledgments

None.

Conflicts of interest

The author declares there is no conflict of interest.

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Citation: Shaikh AY, Wankhade KS. Magnetized dark energy cosmological models with constant deceleration parameter. *Phys Astron Int J.* 2017;1(4):108–113. DOI: 10.15406/paij.2017.01.00020