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Research Article

Statefinder Diagnostic for Variable Modified Chaplygin Gas in LRS Bianchi Type I Universe

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The Locally Rotationally Symmetric (LRS) Bianchi type I cosmological model with variable modified Chaplygin gas having the equation of state $p = A\rho - B/\rho^{\alpha}$, where $0 \leq \alpha \leq 1$, A is a positive constant, and B is a positive function of the average-scale factor $a(t)$ of the universe (i.e., $B = B(a)$) has been studied. It is shown that the equation of state of the variable modified Chaplygin gas interpolates from radiation-dominated era to quintessence-dominated era. The statefinder diagnostic pair (i.e., $\{r, s\}$ parameter) is adopted to characterize different phases of the universe.

1. Introduction

Recent observations of type Ia supernovae team [1, 2] and the WMAP data [3–5] evidenced that the expansion of the universe is accelerating. While explaining these observations, two dark components known as CDM (the pressureless cold dark matter) and DE (the dark energy with negative pressure) are invoked. The CDM contributes $\Omega_{\mathrm{DM}} \sim 0.3$ which gives the theoretical interpretation of the galactic rotation curves and large-scale structure formation. The DE provides $\Omega_{\mathrm{DE}} \sim 0.7$ which causes the acceleration of the distant type Ia supernovae. Different models described this unknown dark sector of the energy content of the universe, starting from the inclusion of exotic components in the context of general relativity to the modifications of the gravitational theory itself, such as a tiny positive cosmological constant [6], quintessence [7, 8], DGP branes [9, 10], the non-linear F(R) models [11–13], and dark energy in brane worlds [14, 15], among many others [16–33] including the review articles [34, 35]. In order to explain anomalous cosmological observations in the cosmic microwave background (CMB) at the largest angles, some authors [36] have suggested cosmological model with anisotropic and viscous dark energy. The binary mixture of perfect fluid and dark energy has been studied for Bianchi type I by [37] and Bianchi type-V by [38]. The anisotropic dark energy has been studied for Bianchi type III in [39] and Bianchi type VIo in [40].

As per [41–43], a unified dark matter—dark energy scenario could be found out, in which these two components (CDM and DE) are different manifestations of a single fluid. Generalised Chaplygin gas is a candidate for such unification which is an exotic fluid with the equation of state $p = -B/\rho^{\alpha}$, where B and α are two parameters are to be determined. It was initially suggested in [44] with $\alpha = 1$ and then generalized in [45] for the case $\alpha \neq 1$.

As per [46], the isotropic pressure p of the cosmological fluid obeys a modified Chaplygin gas equation of state

$$p = A\rho - \frac{B}{\rho^{\alpha}}, \tag{1.1}$$

where $0 \leq A \leq 1$, $0 \leq \alpha \leq 1$, and B is a positive constant.

When $A = 1/3$ and the moving volume of the universe is small (i.e., $\rho \rightarrow \infty$), this equation of state corresponds to a radiation-dominated era. When the density is small (i.e., $\rho \rightarrow 0$), this equation of state corresponds to a cosmological fluid with negative pressure (the dark energy). Generally, the modified Chaplygin gas equation of state corresponds to a mixture of ordinary matter and dark energy. For $\rho = (B/A)^{1/\alpha+1}$ the matter content is pure dust with $p = 0$. The variable Chaplygin gas model was proposed by [47] and constrained using SNeIa 2 "gold" data [48].

Recently, another important form of EOS for variable modified Chaplygin gas [49, 50] is considered as

$$p = A\rho - \frac{B}{\rho^{\alpha}}, \tag{1.2}$$

where $0 \leq \alpha \leq 1$, A is a positive constant, and B is a positive function of the average-scale factor $a(t)$ of the universe (i.e., $B = B(a)$).

Since there are more and more models proposed to explain the cosmic acceleration, it is very desirable to find a way to discriminate between the various contenders in a model independent manner. Sahni et al. [51] proposed a cosmological diagnostic pair $\{r, s\}$ called statefinder, which is defined as

$$r = \frac{\dddot{a}}{aH^3}, \qquad s = \frac{r-1}{3(q-1/2)} \tag{1.3}$$

to differentiate among different forms of dark energy. Here H is the Hubble parameter and q is the deceleration parameter. The two parameters $\{r, s\}$ are dimensionless and are geometrical since they are derived from the cosmic scale factor $a(t)$ alone, though one can rewrite them in terms of the parameters of dark energy and dark matter. This pair gives information about dark energy in a model-independent way, that is, it categorizes dark energy in the context of back-ground geometry only which is not dependent on theory of gravity. Hence, geometrical variables are universal. Therefore, the statefinder is a "geometrical diagnostic" in the sense that it depends upon the expansion factor and hence upon the metric describing space and time. Also, this pair generalizes the well-known geometrical parameters like the Hubble parameter and the deceleration parameter. This pair is algebraically related to the equation of state of dark energy and its first time derivative. The statefinder parameters were introduced to characterize primarily flat universe ($k = 0$) models with cold dark matter (dust) and dark energy.

The statefinder pair $\{1, 0\}$ represents a cosmological constant with a fixed equation of state $w = -1$ and a fixed Newton's gravitational constant. The standard cold dark matter model containing no radiation has been represented by the pair $\{1, 1\}$. The Einstein static universe corresponds to pair $\{\infty, -\infty\}$ [52]. The statefinder diagnostic pair is analyzed for various dark energy candidates including holographic dark energy [53], agegraphic dark energy [54], quintessence [55], dilation dark energy [56], Yang-Mills dark energy [57], viscous dark energy [58], interacting dark energy [59], tachyon [60], modified Chaplygin gas [61], and $f(R)$ gravity [62].

Gorini et al. [63, 64] proved that the simple flat Friedmann model with Chaplygin gas can equivalently be described in terms of a homogeneous minimally coupled scalar field ϕ and a self-interacting potential $V(\phi)$ with effective Lagrangian

$$L_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi). \tag{1.4}$$

Barrow [65, 66] and Kamenshchik et al. [67, 68] have obtained homogeneous scalar field $\phi(t)$ and a potential $V(\phi)$ to describe Chaplygin cosmology.

The Bianchi type V cosmological model with modified Chaplygin gas has been investigated by [69], and Bianchi type-V cosmological model with variable modified Chaplygin gas has been also studied by [70]. In the present paper, the spatially homogeneous and anisotropic LRS Bianchi type I cosmological model with variable modified Chaplygin gas has been investigated. It is shown that the equation of state of this modified model is valid from the radiation era to the quintessence. The statefinder diagnostic pair, that is, $\{r, s\}$ parameter is adopted to characterize different phase of the universe.

2. Metric and Field Equations

The spatially homogeneous and anisotropic LRS Bianchi type I line element can be written as

$$ds^2 = dt^2 - a_1^2 dx^2 - a_2^2\left(dy^2 + dz^2\right), \tag{2.1}$$

where a_1 and a_2 are functions of cosmic time t only.

In view of (2.1), the Einstein field equations are ($8\pi G = c = 1$)

$$\left(\frac{\dot{a}_2}{a_2}\right)^2 + 2\frac{\dot{a}_1\dot{a}_2}{a_1 a_2} = \rho, \tag{2.2}$$

$$2\frac{\ddot{a}_2}{a_2} + \left(\frac{\dot{a}_2}{a_2}\right)^2 = -p, \tag{2.3}$$

$$\frac{\ddot{a}_1}{a_1} + \frac{\ddot{a}_2}{a_2} + \frac{\dot{a}_1\dot{a}_2}{a_1 a_2} = -p, \tag{2.4}$$

where ρ and p are the energy density and pressure, respectively.

The energy conservation equation is

$$\dot{\rho} + \left(\frac{\dot{a}_1}{a_1} + 2\frac{\dot{a}_2}{a_2}\right)(\rho + p) = 0. \tag{2.5}$$

The spatial volume of the universe is defined by

$$V = a^{1/3} = a_1 a_2^2, \tag{2.6}$$

where a is an average-scale factor of the universe.

Let us introduce the variable modified Chaplygin gas having equation of state

$$p = A\rho - \frac{B}{\rho^{\alpha}}, \tag{2.7}$$

where $0 \leq \alpha \leq 1$, A is a positive constant, and B is a positive function of the average scale factor of the universe $a(t)$ (i.e., $B = B(a)$).

Now, assume $B(a)$ is in the form

$$B(a) = B_0 a^{-n} = B_0 V^{-n/3}, \tag{2.8}$$

where $B_0 > 0$ and n are positive constants.

Using (2.5), (2.7), and (2.8), one can obtain

$$\rho = \left[\frac{3(1+\alpha)B_0}{\{3(1+\alpha)(1+A) - n\}}\frac{1}{V^{n/3}} + \frac{C}{V^{(1+\alpha)(1+A)}}\right]^{1/(1+\alpha)}, \tag{2.9}$$

where $C > 0$ is a constant of integration.

For expanding universe, n must be positive, and for positivity of first term in (2.9), we must have $3(1+\alpha)(1+A) > n$.

Case 1. Now, for small values of the scale factors $a_1(t)$ and $a_2(t)$ (refer to [38, 71]), one may have

$$\rho \cong \frac{C^{1/(1+\alpha)}}{V^{(1+A)}} \tag{2.10}$$

which is very large and corresponds to the universe dominated by an equation of state

$$p = A\rho. \tag{2.11}$$

From (2.2)–(2.4), one can get

$$\frac{\ddot{V}}{V} = \frac{3}{2}(\rho - p). \tag{2.12}$$

Using (2.10) and $p = A\rho$, (2.12) yields

$$\int \frac{dV}{\sqrt{3C^{1/(1+\alpha)}V^{(1-A)} + c_1}} = t + t_0, \tag{2.13}$$

where c_1 and t_0 are constants of integration.

For $A = 1/3, c_1 = 0$, and $t_0 = 0$, (2.13) leads to

$$V = Mt^{3/2}, \tag{2.14}$$

where

$$M = \left(\frac{2}{3}\sqrt{3C^{1/(1+\alpha)}}\right)^{3/2}. \tag{2.15}$$

Subtracting (2.3) from (2.4), we obtain

$$\frac{(d/dt)(\dot{a}_1/a_1 - \dot{a}_2/a_2)}{(\dot{a}_1/a_1 - \dot{a}_2/a_2)} + \left(\frac{\dot{a}_1}{a_1} + 2\frac{\dot{a}_2}{a_2}\right) = 0. \tag{2.16}$$

Solving (2.16) and then using (2.6), one may get the values of the scale factors $a_1(t)$ and $a_2(t)$ as

$$\begin{aligned} a_1(t) &= M^{1/3}t^{1/2}\exp\left(-\frac{4\lambda}{3M}t^{-1/2}\right), \\ a_2(t) &= M^{1/3}t^{1/2}\exp\left(\frac{2\lambda}{3M}t^{-1/2}\right), \end{aligned} \tag{2.17}$$

where $\lambda > 0$ is a constant of integration.

From (2.10), the value of the pressure and the energy density of the universe is given by

$$p = \frac{1}{3}\frac{C^{1/(1+\alpha)}}{M^{4/3}t^2}, \qquad \rho \cong \frac{C^{1/(1+\alpha)}}{M^{4/3}t^2}, \tag{2.18}$$

therefore

$$\omega = \frac{p}{\rho} = \frac{1}{3}. \tag{2.19}$$

The Hubble parameter H and the deceleration parameter $[q = (d/dt)(1/H) - 1]$ are found as

$$H = \frac{1}{2t}, \qquad q = 1. \tag{2.20}$$

The universe is decelerating.

From (1.3), the statefinder parameters are found as

$$r = 3, \qquad s = \frac{1}{3}. \tag{2.21}$$

Case 2. Now, for large values of the scale factors $a_1(t)$ and $a_2(t)$ (refer to [38, 71]), one may have

$$\rho = \left(\frac{3(1+\alpha)B_0}{\{3(1+\alpha)(1+A) - n\}}\right)^{1/(1+\alpha)} V^{-n/3(1+\alpha)}, \tag{2.22}$$

and the pressure is given by

$$p = \left(-1 + \frac{n}{3(1+\alpha)}\right)\rho. \tag{2.23}$$

Using (2.22) and (2.23) in (2.12), we get

$$V = Dt^{6(1+\alpha)/n}, \tag{2.24}$$

where

$$D = \left[\frac{n}{6(1+\alpha)}\right]^{6(1+\alpha)/n} \left[\frac{3}{1+\alpha}\right]^{3(1+\alpha)/n/n} \left[\frac{3(1+\alpha)B_0}{3(1+\alpha)(1+A) - n}\right]^{3/n}. \tag{2.25}$$

Solving (2.16) and then using (2.24), one may get the values of the scale factors $a_1(t)$ and $a_2(t)$ as

$$a_1(t) = D^{1/3} t^{2(1+\alpha)/n} \exp\left[\frac{2\beta n}{3D(n - 6(1+\alpha))} t^{n-6(1+\alpha)/n}\right], \tag{2.26}$$

$$a_2(t) = D^{1/3} t^{2(1+\alpha)/n} \exp\left[\frac{-\beta n}{3D(n - 6(1+\alpha))} t^{n-6(1+\alpha)/n}\right], \tag{2.27}$$

where $\beta > 0$ is a constant of integration.

The Hubble parameter H and the deceleration parameter $[q = (d/dt)(1/H) - 1]$ are found as

$$H = \frac{2(1+\alpha)}{n}\frac{1}{t}, \qquad q = \frac{n}{2(1+\alpha)} - 1. \tag{2.28}$$

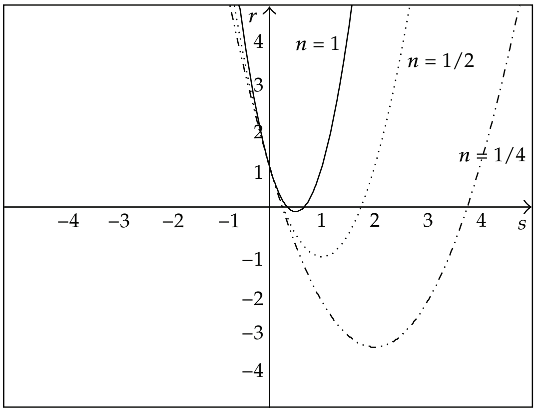

Figure 1: variation r against s for different values of $n(= 1/4, 1/2, 1)$.

From (1.3), the statefinder parameters are found as

$$r = 1 - \frac{3}{2(1+\alpha)} + \frac{n}{2(1+\alpha)^2}, \qquad s = \frac{1}{3(1+\alpha)}. \tag{2.29}$$

The relation (Figure 1) between the statefinder parameters r and s is

$$r = 1 - \frac{9}{2}s + \frac{9n}{2}s^2. \tag{2.30}$$

To describe the variable modified Chaplygin gas cosmology, consider the energy density ρ_ϕ and pressure p_ϕ corresponding to a scalar field ϕ having a self-interacting potential $v(\phi)$ as

$$\begin{aligned}
\rho_\phi &= \frac{1}{2}\dot{\phi}^2 + v(\phi) = \rho = \left[\frac{3(1+\alpha)B_0}{\{3(1+\alpha)(1+A)-n\}}\frac{1}{V^{n/3}} + \frac{C}{V^{(1+\alpha)(1+A)}}\right]^{1/(1+\alpha)} \\
p_\phi &= \frac{1}{2}\dot{\phi}^2 - v(\phi) \\
&= A\rho - \frac{B_0 V^{-n/3}}{\rho^\alpha} = A\left[\frac{3(1+\alpha)B_0}{\{3(1+\alpha)(1+A)-n\}}\frac{1}{V^{n/3}} + \frac{C}{V^{(1+\alpha)(1+A)}}\right]^{1/(1+\alpha)} \\
&\quad - B_0 V^{-n/3}\left[\frac{3(1+\alpha)B_0}{\{3(1+\alpha)(1+A)-n\}}\frac{1}{V^{n/3}} + \frac{C}{V^{(1+\alpha)(1+A)}}\right]^{-\alpha/(1+\alpha)}.
\end{aligned} \tag{2.31}$$

From (2.31), we have

$$\dot{\phi}^2 = (1+A)\left[\frac{3(1+\alpha)B_0}{\{3(1+\alpha)(1+A)-n\}}\frac{1}{V^{n/3}} + \frac{C}{V^{(1+\alpha)(1+A)}}\right]^{1/(1+\alpha)} - B_0 V^{-n/3}\left[\frac{3(1+\alpha)B_0}{\{3(1+\alpha)(1+A)-n\}}\frac{1}{V^{n/3}} + \frac{C}{V^{(1+\alpha)(1+A)}}\right]^{-\alpha/(1+\alpha)},$$

$$v(\phi) = \frac{(1-A)}{2}\left[\frac{3(1+\alpha)B_0}{\{3(1+\alpha)(1+A)-n\}}\frac{1}{V^{n/3}} + \frac{C}{V^{(1+\alpha)(1+A)}}\right]^{1/(1+\alpha)} + \frac{B_0 V^{-n/3}}{2}\left[\frac{3(1+\alpha)B_0}{\{3(1+\alpha)(1+A)-n\}}\frac{1}{V^{n/3}} + \frac{C}{V^{(1+\alpha)(1+A)}}\right]^{-\alpha/(1+\alpha)}. \tag{2.32}$$

When kinetic term is small compared to the potential, we obtain

$$\rho \approx V, \qquad p \approx -V, \tag{2.33}$$

therefore

$$\omega = p/\rho = -1. \tag{2.34}$$

We know that different possibilities can be distinguished for nature of dark energy by its equation of state characterized by $\omega = p/\rho$. (The equation of state parameter for radiation is simply $\omega_r = 1/3$, whereas for matter, it is $\omega_m = 0$). The equation (2.33) recovers the constant solution for dark energy with $\omega = -1$. This is consistent with the central value determined by WMAP as

$$-0.33 < 1 + \omega_0 < 0.21, \quad \text{for value of } \omega \text{ today}. \tag{2.35}$$

In both cases (Cases 1 and 2), from (2.17), (2.26), and (2.27), it is observed that, when $t \to \infty$, we get $a(t) \to \infty$, which is also supported by recent observations of supernovae Ia [1, 2] and WMAP [5]. Therefore, the present model is free from finite time future singularity.

3. Conclusion

The spatially homogeneous and anisotropic LRS Bianchi type I cosmological model with variable modified Chaplygin gas has been studied. It is noted that the equation of state for this model is valid from the radiation era to the quintessence. It reduces to dark energy for small kinetic energy. In first case, it is observed that initially the universe is decelerating and later on (in the second case) it is accelerating which is consistent with the present day astronomical observations. The present model is free from finite time future singularity. The statefinder diagnostic pair (i.e., $\{r, s\}$ parameter) is adopted to differentiate among different forms of dark energy.

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