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 $\Omega_{\text{DM}} \sim 0.3$ which gives the theoretical interpretation of the galactic rotation curves and large-scale structure formation. The DE provides $\Omega_{\text{DE}} \sim 0.7$ 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 VI₀ 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

$$p = A\rho - \frac{B}{\rho^\alpha}, \quad (1.1)$$

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

$$p = A\rho - \frac{B}{\rho^\alpha}, \quad (1.2)$$

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

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

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

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

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

$$ds^2 = dt^2 - a_1^2 dx^2 - a_2^2 (dy^2 + dz^2), \quad (2.1)$$

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

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

$$\left(\frac{\dot{a}_2}{a_2}\right)^2 + 2\frac{\dot{a}_1\dot{a}_2}{a_1a_2} = \rho, \quad (2.2)$$

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

$$\frac{\ddot{a}_1}{a_1} + \frac{\ddot{a}_2}{a_2} + \frac{\dot{a}_1\dot{a}_2}{a_1a_2} = -p, \quad (2.4)$$

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

The energy conservation equation is

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

The spatial volume of the universe is defined by

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

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

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

$$p = A\rho - \frac{B}{\rho^\alpha}, \quad (2.7)$$

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

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

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

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

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

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

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

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

$$p = A\rho. \quad (2.11)$$

From (2.2)–(2.4), one can get

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

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

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

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

$$V = Mt^{3/2}, \quad (2.14)$$

where

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

Subtracting (2.3) from (2.4), we obtain

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

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

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

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

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

therefore

$$\omega = \frac{p}{\rho} = \frac{1}{3}. \quad (2.19)$$

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

$$H = \frac{1}{2t}, \quad q = 1. \quad (2.20)$$

The universe is decelerating.

From (1.3), the statefinder parameters are found as

$$r = 3, \quad s = \frac{1}{3}. \quad (2.21)$$

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

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

and the pressure is given by

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

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

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

where

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

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

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

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

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

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

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

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

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

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

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

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

From (2.31), we have

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

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

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

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 $t \rightarrow \infty$, we get $a(t) \rightarrow \infty$, 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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References

- [1] S. Perlmutter, G. Aldering, G. Goldhaber et al., "Measurements of Ω and Λ from 42 high-redshift Supernovae," *Astrophysical Journal Letters*, vol. 517, no. 2, pp. 565–586, 1999.
- [2] A. G. Riess, A. V. Filippenko, P. Challis et al., "Observational evidence from supernovae for an accelerating universe and a cosmological constant," *Astronomical Journal*, vol. 116, no. 3, pp. 1009–1038, 1998.
- [3] P. De Bernardis, P. A. R. Ade, J. J. Bock et al., "A flat Universe from high-resolution maps of the cosmic microwave background radiation," *Nature*, vol. 404, no. 6781, pp. 955–959, 2000.
- [4] S. Hanany, P. Ade, A. Balbi et al., "MAXIMA-1: a measurement of the cosmic microwave background anisotropy on angular scales of $10'$ – 5° ," *Astrophysical Journal Letters*, vol. 545, no. 1, pp. L5–L9, 2000.
- [5] D. N. Spergel, R. Bean, O. Doré et al., "Three-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: implications for cosmology," *Astrophysical Journal*, vol. 170, no. 2, pp. 377–408, 2007.
- [6] R. R. Caldwell, R. Dave, and P. J. Steinhardt, "Cosmological imprint of an energy component with general equation of state," *Physical Review Letters*, vol. 80, no. 8, pp. 1582–1585, 1998.
- [7] A. R. Liddle and R. J. Scherrer, "Classification of scalar field potentials with cosmological scaling solutions," *Physical Review D*, vol. 59, Article ID 023509, 1999.
- [8] P. J. Steinhardt, L. Wang, and I. Zlatev, "Cosmological tracking solutions," *Physical Review D*, vol. 59, Article ID 123504, 1999.
- [9] G. Dvali, G. Gabadadze, and M. Porrati, "Metastable gravitons and infinite volume extra dimensions," *Physics Letters, Section B*, vol. 484, no. 1-2, pp. 112–118, 2000.
- [10] C. Deffayet, "Cosmology on a brane in Minkowski bulk," *Physics Letters, Section B*, vol. 502, pp. 199–208, 2001.
- [11] S. Capozziello, S. Carloni, and A. Troisi, "Quintessence without scalar fields," <http://arxiv.org/abs/astro-ph/0303041>.
- [12] S. M. Carroll, V. Duvvuri, M. Trodden, and M. S. Turner, "Is cosmic speed-up due to new gravitational physics?" *Physical Review D*, vol. 70, no. 4, Article ID 043528, 2004.
- [13] S. Nojiri and S. D. Odintsov, "Modified gravity with negative and positive powers of curvature: unification of inflation and cosmic acceleration," *Physical Review D*, vol. 68, Article ID 123512, 2003.
- [14] P. K. Townsend and M. N. R. Wohlfarth, "Accelerating cosmologies from compactification," *Physical Review Letters*, vol. 91, no. 6, Article ID 061302, 4 pages, 2003.
- [15] G. W. Gibbons, "Aspects of supergravity theories," in *Supersymmetry, Supergravity and Related Topics*, F. del Aguila, J. A. de Azcarraga, and L. E. Ibanez, Eds., pp. 346–351, World Scientific, 1985.
- [16] J. Maldacena and C. Nuñez, "Supergravity description of field theories on curved manifolds and a no go theorem," *International Journal of Modern Physics A*, vol. 16, no. 5, pp. 822–855, 2001.
- [17] N. Ohta, "Accelerating cosmologies from spacelike branes," *Physical Review Letters*, vol. 91, no. 6, Article ID 061303, 4 pages, 2003.
- [18] M. N. R. Wohlfarth, "Accelerating cosmologies and a phase transition in M-theory," *Physics Letters, Section B*, vol. 563, no. 1-2, pp. 1–5, 2003.
- [19] S. Roy, "Accelerating cosmologies from M/string theory compactifications," *Physics Letters, Section B*, vol. 567, no. 3-4, pp. 322–329, 2003.
- [20] J. K. Webb, M. T. Murphy, V. V. Flambaum et al., "Further evidence for cosmological evolution of the fine structure constant," *Physical Review Letters*, vol. 87, no. 9, Article ID 091301, pp. 1–4, 2001.
- [21] J. M. Cline and J. Vinet, "Problems with time-varying extra dimensions or "Cardassian expansion" as alternatives to dark energy," *Physical Review D*, vol. 68, Article ID 025015, 2003.
- [22] N. Ohta, "A study of accelerating cosmologies from superstring/M theories," *Progress of Theoretical Physics*, vol. 110, no. 2, pp. 269–283, 2003.

- [23] N. Ohta, "Accelerating cosmologies and inflation from M/superstring theories," *International Journal of Modern Physics A*, vol. 20, no. 1, pp. 1–40, 2005.
- [24] C. M. Chen et al., "Hyperbolic space cosmologies," *Journal of High Energy Physics*, vol. 10, article 058, 2003.
- [25] E. Bergshoeff, A. Collinucci, U. Gran, M. Nielsen, and D. Roest, "Transient quintessence from group manifold reductions or how all roads lead to Rome," *Classical and Quantum Gravity*, vol. 21, no. 8, pp. 1947–1969, 2004.
- [26] Y. Gong and A. Wang, "Acceleration from M theory and fine-tuning," *Classical and Quantum Gravity*, vol. 23, pp. 3419–3426, 2006.
- [27] I. P. Neupane and D. L. Wiltshire, "Accelerating cosmologies from compactification with a twist," *Physics Letters, Section B*, vol. 619, no. 3–4, pp. 201–207, 2005.
- [28] I. P. Neupane and D. L. Wiltshire, "Cosmic acceleration from M theory on twisted spaces," *Physical Review D*, vol. 72, Article ID 083509, 2005.
- [29] K.-I. Maeda and N. Ohta, "Inflation from superstring and M-theory compactification with higher order corrections," *Physical Review D*, vol. 71, no. 6, Article ID 063520, pp. 1–27, 2005.
- [30] I. P. Neupane, "Accelerating universes from compactification on a warped conifold," *Physical Review Letters*, vol. 98, no. 6, Article ID 061301, 2007.
- [31] Y. Gong, A. Wang, and Q. Wu, "Cosmological constant and late transient acceleration of the universe in the Horava-Witten heterotic M-theory on S^1 / Z_2 ," *Physics Letters, Section B*, vol. 663, no. 3, pp. 147–151, 2008.
- [32] P. R. Pereira, M. F. A. Da Silva, and R. Chan, "Anisotropic self-similar cosmological model with dark energy," *International Journal of Modern Physics D*, vol. 15, no. 7, pp. 991–999, 2006.
- [33] C. F. C. Brandt, R. Chan, M. A. F. Da Silva, and J. F. V. Da Rocha, "Inhomogeneous dark energy and cosmological acceleration," *General Relativity and Gravitation*, vol. 39, no. 10, pp. 1675–1687, 2007.
- [34] E. J. Copeland, M. Sami, and S. Tsujikawa, "Dynamics of dark energy," *International Journal of Modern Physics D*, vol. 15, no. 11, pp. 1753–1935, 2006.
- [35] T. Padmanabhan, "Dark energy and gravity," *General Relativity and Gravitation*, vol. 40, no. 2–3, pp. 529–564, 2008.
- [36] T. Koivisto and D. F. Mota, "Anisotropic dark energy: dynamics of the background and perturbations," *Journal of Cosmology and Astroparticle Physics*, vol. 06, no. 6, article 018, 2008.
- [37] S. Bijan, *Chinese Journal of Physics*, vol. 43, p. 1035, 2005.
- [38] T. Singh and R. Chaubey, "Bianchi type-V cosmological models with perfect fluid and dark energy," *Astrophysics and Space Science*, vol. 319, no. 2–4, pp. 149–154, 2009.
- [39] O. Akarsu and C. B. Kilinç, "Bianchi type III models with anisotropic dark energy," *General Relativity and Gravitation*, vol. 42, no. 4, pp. 763–775, 2010.
- [40] K. S. Adhav, A. S. Bansod, S. L. Munde, and R. G. Nakwal, "Bianchi type-VI0 cosmological models with anisotropic dark energy," *Astrophysics and Space Science*, vol. 332, no. 2, pp. 497–502, 2011.
- [41] T. Matos and L. A. Ureña-López, "Quintessence and scalar dark matter in the Universe," *Classical and Quantum Gravity*, vol. 17, pp. L75–L81, 2000.
- [42] C. Wetterich, "Cosmon dark matter?" *Physical Review D*, vol. 65, no. 12, Article ID 123512, 2002.
- [43] T. Padmanabhan and T. R. Choudhury, "Can the clustered dark matter and the smooth dark energy arise from the same scalar field?" *Physical Review D*, vol. 66, Article ID 081301, 2002.
- [44] A. Kamenshchik, U. Moschella, and V. Pasquier, "An alternative to quintessence," *Physics Letters, Section B*, vol. 511, no. 2–4, pp. 265–268, 2001.
- [45] M. C. Bento, O. Bertolami, and A. A. Sen, "Generalized Chaplygin gas, accelerated expansion, and dark-energy-matter unification," *Physical Review D*, vol. 66, Article ID 043507, 2002.
- [46] U. Debnath, A. Banerjee, and S. Chakraborty, "Role of modified Chaplygin gas in accelerated universe," *Classical and Quantum Gravity*, vol. 21, no. 23, pp. 5609–5617, 2004.
- [47] Z.-K. Guo and Y.-Z. Zhang, "Cosmology with a variable Chaplygin gas," *Physics Letters, Section B*, vol. 645, no. 4, pp. 326–329, 2007.
- [48] A. G. Riess, L.-G. Sjolger, J. Tonry et al., "Type Ia supernova discoveries at $z > 1$ from the hubble space telescope: evidence for past deceleration and constraints on dark energy evolution," *Astrophysical Journal Letters*, vol. 607, no. 2 I, pp. 665–687, 2004.
- [49] U. Debnath, "Variable modified Chaplygin gas and accelerating universe," *Astrophysics and Space Science*, vol. 312, no. 3–4, pp. 295–299, 2007.

- [50] M. Jamil and M. A. Rashid, "Interacting modified variable Chaplygin gas in a non-flat universe," *European Physical Journal C*, vol. 58, pp. 111–114, 2008.
- [51] V. Sahni, T. D. Saini, A. A. Starobinsky, and U. Alam, "Statefinder—a new geometrical diagnostic of dark energy," *JETP Letters*, vol. 77, no. 5, pp. 201–206, 2003.
- [52] U. Debnath, "Emergent universe and the phantom tachyon model," *Classical and Quantum Gravity*, vol. 25, Article ID 205019, 2008.
- [53] X. Zhang, "Statefinder diagnostic for holographic dark energy model," *International Journal of Modern Physics D*, vol. 14, no. 9, pp. 1597–1606, 2005.
- [54] H. Wei and R.-G. Cai, "Statefinder diagnostic and w - w' analysis for the agegraphic dark energy models without and with interaction," *Physics Letters, Section B*, vol. 655, pp. 1–6, 2007.
- [55] X. Zhang, "Statefinder diagnostic for coupled quintessence," *Physics Letters, Section B*, vol. 611, no. 1-2, pp. 1–7, 2005.
- [56] Z. G. Huang, X. M. Song, H. Q. Lu, and W. Fang, "Statefinder diagnostic for dilaton dark energy," *Astrophysics and Space Science*, vol. 315, no. 1-4, pp. 175–179, 2008.
- [57] W. Zhao, "Statefinder diagnostic for the yang-mills dark energy model," *International Journal of Modern Physics D*, vol. 17, pp. 1245–1254, 2008.
- [58] M.-G. Hu and X.-H. Meng, "Bulk viscous cosmology: statefinder and entropy," *Physics Letters, Section B*, vol. 635, no. 4, pp. 186–194, 2006.
- [59] W. Zimdahl and D. Pavón, "Statefinder parameters for interacting dark energy," *General Relativity and Gravitation*, vol. 36, no. 6, pp. 1483–1491, 2004.
- [60] Y. Shao and Y. Gui, "Statefinder parameters for tachyon dark energy model," *Modern Physics Letters A*, vol. 23, pp. 65–71, 2008.
- [61] W. Chakraborty and U. Debnath, "Is modified Chaplygin gas along with barotropic fluid responsible for acceleration of the universe?" *Modern Physics Letters A*, vol. 22, no. 24, pp. 1805–1812, 2007.
- [62] S. Li, "Statefinder diagnosis for the Palatini $f(R)$ gravity theories," <http://arxiv.org/abs/1002.3867>.
- [63] V. Gorini, "The Chaplygin gas as a model for dark energy," <http://arxiv.org/abs/gr-qc/0403062>.
- [64] V. Gorini, A. Kamenshchik, and U. Moschella, "Can the Chaplygin gas be a plausible model for dark energy?" *Physical Review D*, vol. 67, Article ID 063509, 2003.
- [65] J. D. Barrow, "String-driven inflationary and deflationary cosmological models," *Nuclear Physics, Section B*, vol. 310, no. 3-4, pp. 743–763, 1988.
- [66] J. D. Barrow, "Graduated inflationary universes," *Physics Letters, Section B*, vol. 235, pp. 40–43, 1990.
- [67] A. Kamenshchik, U. Moschella, and V. Pasquier, "An alternative to quintessence," *Physics Letters, Section B*, vol. 511, no. 2-4, pp. 265–268, 2001.
- [68] V. Gorini, A. Kamenshchik, U. Moschella, and V. Pasquier, "Tachyons, scalar fields, and cosmology," *Physical Review D*, vol. 69, no. 12, Article ID 123512, 2004.
- [69] K. S. Adhav, "Statefinder diagnostic for modified Chaplygin gas in Bianchi type-V universe," *European Physical Journal Plus*, vol. 126, no. 5, pp. 1–9, 2011.
- [70] K. S. Adhav, "Statefinder diagnostic for variable modified Chaplygin gas in Bianchi type-V universe," *Astrophysics and Space Science*, vol. 335, no. 2, pp. 611–617, 2011.
- [71] S. Ram, M. Zeyauddin, and C. P. Singh, "Generalized chaplygin gas dominated anisotropic bianchi type-i cosmological models," *International Journal of Theoretical Physics*, vol. 48, no. 1, pp. 50–60, 2009.