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ORIGINAL ARTICLE

An interacting and non-interacting two-fluid scenario for dark energy in FRW universe with constant deceleration parameter

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Abstract In this paper we study the evolution of the dark energy parameter within the scope of a spatially homogeneous and isotropic FRW universe filled with barotropic fluid and dark energy. The scale factor is considered as a power law function of time which yields a constant deceleration parameter. We consider the case when the dark energy is minimally coupled to the perfect fluid as well as direct interaction with it. The cosmic jerk parameter in our derived models is consistent with the recent data of astrophysical observations. It is concluded that in non-interacting case, all the three open, close and flat universes cross the phantom region whereas in interacting case only open and flat universes cross the phantom region. We find that during the evolution of the universe, the equation of state (EoS) for dark energy ω_D changes from $\omega_D > -1$ to $\omega_D < -1$, which is consistent with recent observations.

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1 Introduction

In recent years, observations of distant Supernovae (SNe Ia) (Perlmutter et al. 1997, 1998, 1999; Riess et al. 1998, 2000; Garnavich et al. 1998a, 1998b; Schmidt et al. 1998; Tonry et al. 2003; Clocchiatti et al. 2006), fluctuation of cosmic microwave background radiation (CMBR) (de Bernardis et al. 1998; Hanany et al. 20000), large scale structure (LSS) (Spergel et al. 2003; Tegmark et al. 2004), Sloan Digital Sky Survey (SDSS) (Seljak et al. 2005; Adelman-McCarthy et al. 2006), WMAP (Bennett et al. 2003) and Chandra X-ray observatory (Allen et al. 2004) by means of ground and altitudinal experiments showed that our Universe is spatially flat and expanding with acceleration. Therefore some form of dark energy whose fractional energy density is about $\Omega_{DE} = 0.70$ must exist in the Universe to drive this acceleration. This fact can be put in agreement with the theory, if one assumes that the Universe is basically filled with so-called dark energy. Evolution of the equation of state (EoS) of dark energy $\omega_D = \frac{p_D}{\rho_D}$ transfers from $\omega_D > -1$ in the near past (quintessence region) to $\omega_D < -1$ at recent stage (phantom region) (Alam et al. 2004a, 2004b; Feng et al. 2005; Huterer and Cooray 2005; Chang et al. 2006; Sahni and Shtanov 2003). So another cosmological coincidence problem may be proposed: why $\omega_D = 1$ crossing is occurred at the present time (Wei and Cai 2006a, 2006b). In Vikman (2005), it was shown that $\omega_D = 1$ crossing in models including matter and phantom scalar field is either impossible or unstable with respect to cosmological perturbations. However, this transition may be possible for scalar-tensor theories (Perivolaropoulos 2005), multi-field models (Guo et al. 2005a; Hu 2005; Wei and

Cai 2006a, 2006b; Zhang et al. 2006), and coupled dark energy models with specific couplings (Guo et al. 2005b; Nojiri et al. 2005; Gumjudpai et al. 2005). When SNe results are combined with five-year WMAP, it is observed that ω_D falls between -1.38 and 0.86 (Hinshaw et al. 2009; Komatsu et al. 2009; Perlmutter et al. 2003).

The Einstein's field equations are a coupled system of highly nonlinear differential equations and we seek physical solutions to the field equations for their application in cosmology and astrophysics. In order to solve the field equations we normally assume a form of the matter content or that space-time admits killing vector symmetries (Kramer et al. 1980). Solutions to the field equations may also be generated by applying a law of variation for Hubble's parameter which was proposed by Berman (1983). It is interesting to observe that the law yields a constant value of deceleration parameter (DP). The variation of Hubble's law as assumed is not inconsistent with observations and has the advantage of providing simple functional forms of the scale factor. In simplest case the Hubble law yields a constant value of the DP. The cosmological models with constant deceleration parameter (CDP) may be divided into two categories. The first category of models with CDP is that of models where the cosmic expansion is driven by big bang impulse; all the matter and radiation energy is proposed at the big bang epoch and the universe has started with singular origin. In the second category of models with CDP, the universe has a non-singular origin and the cosmic expansion is driven by the creation of matter particles. It is worth observing that most of the well-known models of Einstein's theory and Brans-Duke theory with curvature parameter $k = 0$, including inflationary models, are models with CDP. It also measures the deviation from linearity of growth of the scale factor. Cosmological models with a CDP have been studied by Berman (1983), Berman and Gomide (1988), Johri and Desikan (1994a, 1994b), Singh and Desikan (1997), Maharaj and Naidoo (1993), Pradhan et al. (2001), Pradhan and Vishwakarma (2002), Pradhan and Aotemshi (2002), Pradhan and Jotania (2010), Pradhan and Singh (2011), Saha and Rikhvitsky (2006), Saha (2006), Singh and Kumar (2006, 2007a, 2007b), Singh and Chaubey (2006, 2007), Zeyauddin and Ram (2009), Singh and Baghel (2009) and others. Recently, Akarsu and Kilinc (2010a, 2010b), Pradhan et al. (2010), Pradhan and Amirhashchi (2011), Yadav and Yadav (2011) have studied dark energy models in Bianchi type space-times and FRW universe with CDP.

Dark energy models with higher derivative terms were constructed by Zhang and Liu (2009). The cosmological evolution of a two-field dilaton model of dark energy was investigated by Liang et al. (2009). Viscous dark energy models with variable G and Λ were studied by Arbab (2008). The modified Chaplygin gas with interaction between holographic dark energy and dark matter was investigated by Wang et al. (2009). The tachyon cosmology in interacting and non-interacting cases in non-flat FRW Universe was studied by Setare et al. (2009), Setare and Saridakis (2009). Setare (2007a, 2007b, 2007c) also studied the dark energy models in different contexts. Recently Amirhashchi et al. (2011a, 2011b, 2011c) have studied two-fluid dark energy models in FRW universe with variable deceleration parameter. Motivated by the above discussions, in this paper, we have considered the evolution of the dark energy parameter within the scope of a spatially flat and isotropic FRW universe filled with barotropic fluid and dark energy by considering the CDP. The introduction and motivation are laid down in Sect. 1. The metric and the field equations are given in Sect. 2. In Sect. 3, non-interacting two-fluid model is discussed where as Sect. 4 deals with interacting two-fluid model with their physical application. Concluding remarks are given in the last Sect. 5.

2 The metric and field equations

We consider the spatially homogeneous and isotropic Friedmann-Robertson-Walker (FRW) metric as

$$ds^2 = -dt^2 + a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right], \tag{1}$$

where $a(t)$ is the scale factor and the curvature constant k is $-1, 0, +1$ respectively for open, flat and close models of the universe. $d\Omega^2 = d\theta^2 + \sin^2\theta + \sin^2\theta d\phi^2$ is the line element on the unit two-sphere.

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

$$R_i^j - \frac{1}{2}R\delta_i^j = -T_i^j, \tag{2}$$

where the symbols have their usual meaning and T_i^j is the two fluid energy-momentum tensor consisting of dark field and barotropic fluid.

In a co-moving coordinate system, Einstein's field equations (2) for the line element (1) lead to

$$p_{tot} = -\left(2\frac{\ddot{a}}{a} + \frac{\dot{a}^2}{a^2} + \frac{k}{a^2}\right), \tag{3}$$

and

$$\rho_{tot} = 3\left(\frac{\dot{a}^2}{a^2} + \frac{k}{a^2}\right), \tag{4}$$

where $p_{tot} = p_m + p_D$ and $\rho_{tot} = \rho_m + \rho_D$. Here p_m and ρ_m are pressure and energy density of barotropic fluid and p_D & ρ_D are pressure and energy density of dark fluid respectively.

The Bianchi identity $G^{;j}_{ij}=0$ leads to $T^{;j}_{ij}=0$ which yields

$$\dot{\rho}_{tot}+3\frac{\dot{a}}{a}(\rho_{tot}+p_{tot})=0. \tag{5}$$

The EoS of the barotropic fluid and dark field are given by

$$\omega_m=\frac{p_m}{\rho_m}, \tag{6}$$

and

$$\omega_D=\frac{p_D}{\rho_D}, \tag{7}$$

respectively.

In the following sections we deal with two cases, (i) non-interacting two-fluid model and (ii) interacting two-fluid model.

3 Non-interacting two-fluid model

In this section we assume that two fluid do not interact with each other. Therefor, the general form of conservation equation (5) leads us to write the conservation equation for the dark and barotropic fluid separately as,

$$\dot{\rho}_m+3\frac{\dot{a}}{a}(\rho_m+p_m)=0, \tag{8}$$

and

$$\dot{\rho}_D+3\frac{\dot{a}}{a}(\rho_D+p_D)=0. \tag{9}$$

Integration of (5) leads to

$$\rho_m=\rho_0 a^{-3(1+\omega_m)}. \tag{10}$$

By using (10) in (3) and (4), we first obtain the ρ_D and p_D in term of scale factor $a(t)$

$$\rho_D=3\left(\frac{\dot{a}^2}{a^2}+\frac{k}{a^2}\right)-\rho_0 a^{-3(1+\omega_m)}, \tag{11}$$

and

$$p_D=-\left(2\frac{\ddot{a}}{a}+\frac{\dot{a}^2}{a^2}+\frac{k}{a^2}\right)-\rho_0\omega_m a^{-3(1+\omega_m)}. \tag{12}$$

Now we take following *ansatz* for the scale factor, where increase in term of time evolution

$$a(t)=(t-t_0)^n, \tag{13}$$

where n is a positive constant. By using this scale factor in (11) and (12), the ρ_D and p_D are obtained as

$$\rho_D=\frac{3n^2}{(t-t_0)^2}+\frac{3k}{(t-t_0)^{2n}}-\rho_0(t-t_0)^{-3n(1+\omega_m)}, \tag{14}$$

and

$$p_D=-\left[\frac{n(3n-2)}{(t-t_0)^2}+\frac{k}{(t-t_0)^{2n}}+\rho_0\omega_m(t-t_0)^{-3n(1+\omega_m)}\right], \tag{15}$$

respectively. By using (14) and (15) in (7), we can find the equation of state of dark field in term of time as

$$\omega_D=-\left[\frac{\frac{n(3n-2)}{(t-t_0)^2}+\frac{k}{(t-t_0)^{2n}}+\rho_0\omega_m(t-t_0)^{-3n(1+\omega_m)}}{\frac{3n^2}{(t-t_0)^2}+\frac{3k}{(t-t_0)^{2n}}-\rho_0(t-t_0)^{-3n(1+\omega_m)}}\right]. \tag{16}$$

The behavior of EoS in term of cosmic time t is shown in Fig. 1. It is observed that though for open, close and flat universe the EoS parameter is a increasing function of time, the rapidity of its growth at the early stage depends on the type the universe, while later on it tends to the same constant value independent to it.

The expressions for the matter-energy density Ω_m and dark-energy density Ω_D are given by

$$\Omega_m=\frac{\rho_m}{3H^2}=\frac{\rho_0}{3n^2}(t-t_0)^{-3n(1+\omega_m)+2}, \tag{17}$$

and

$$\Omega_D=\frac{\rho_D}{3H^2}=1+\frac{k}{n^2(t-t_0)^{2(n-1)}}-\frac{\rho_0}{3n^2}(t-t_0)^{-3n(1+\omega_m)+2}, \tag{18}$$

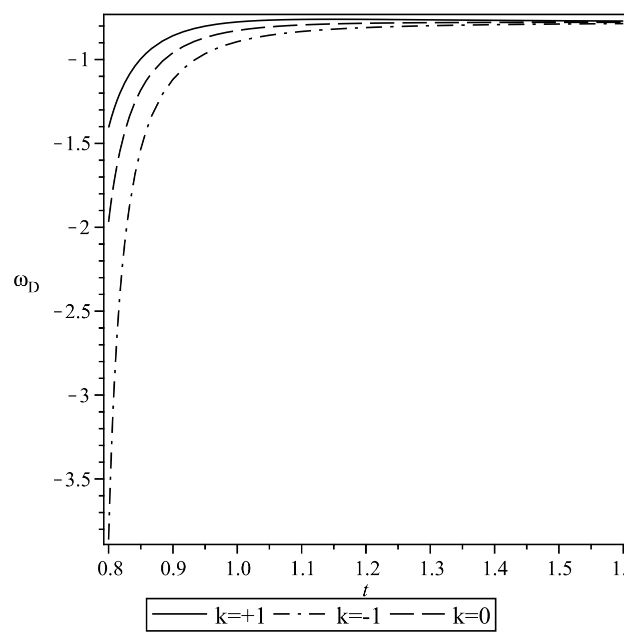

Fig. 1 The plot of EoS parameter vs. t for $\rho_0=1$, $\omega_m=0.5$, $n=3$ in non-interacting two-fluid model

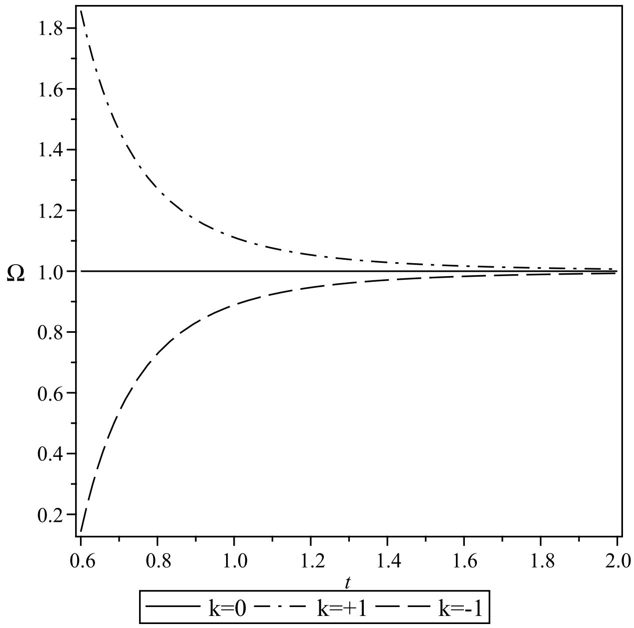

Fig. 2 The plot of density parameter (Ω) vs. t for $n=3$ in non-interacting two-fluid model

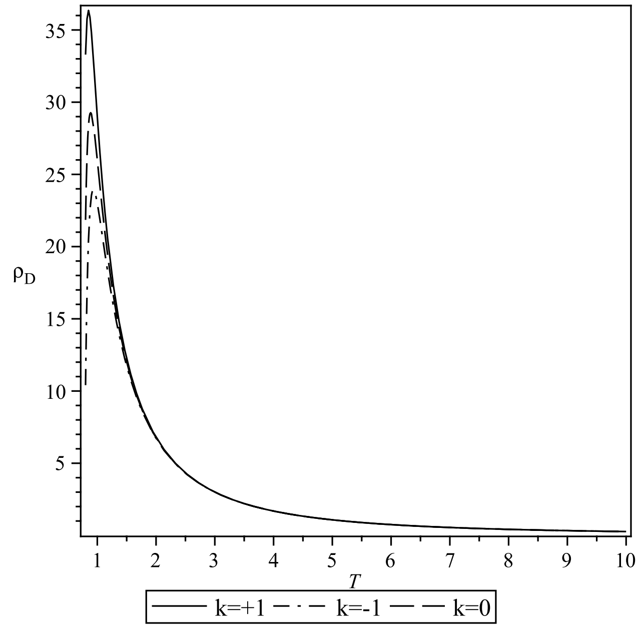

Fig. 3 The plot of ρ_D vs. t for $\rho_0=1$, $n=3$, $\omega_m=0.5$ in non-interacting two-fluid model

respectively. Equations (17) and (18) reduce to

$$\Omega=\Omega_m+\Omega_D=1+\frac{k}{n^2(t-t_0)^{2(n-1)}}. \tag{19}$$

From the right hand side of (19) it is clear that in flat universe ($k=0$), $\Omega=1$ and in open universe ($k=-1$), $\Omega<1$ and in close universe ($k=+1$), $\Omega>1$. But at late time we see for all flat, open and close universes $\Omega\to 1$. This result is also compatible with the observational results. Since our model predicts a flat universe for large times and the present-day universe is very close to flat, so the derived model is also compatible with the observational results. The variation of density parameter with cosmic time has been shown in Fig. 2.

We define the deceleration parameter q as usual, i.e.

$$q=-\frac{\ddot{a}a}{\dot{a}^2}=-\frac{\ddot{a}}{aH^2}. \tag{20}$$

Using (3) and (4), we may rewrite (20) as

$$q=\frac{1}{6H^2}[\rho_m(1+3\omega_m)+\rho_D(1+3\omega_D)]. \tag{21}$$

On the other hand, using (13) into (20), we find

$$q=\frac{1-n}{n}. \tag{22}$$

From (22), we observe that $q<0$ if $n>1$ or $n<0$ and $q>0$ if $0<n<1$.

Figure 3 depicts the energy density for dark fluid ρ_D versus t. It is observed that ρ_D decreases with increase of time in all the three open, close and flat universes. Figure 4 shows the plot between the pressure for DE p_D and t. It is observed that p_D is always negative in all open, close and flat universes as aspected. The behaviour of ρ_m and p_m are shown in Fig. 5. It is observed that both are positive decreasing function of time and converges to zero as $t\to\infty$.

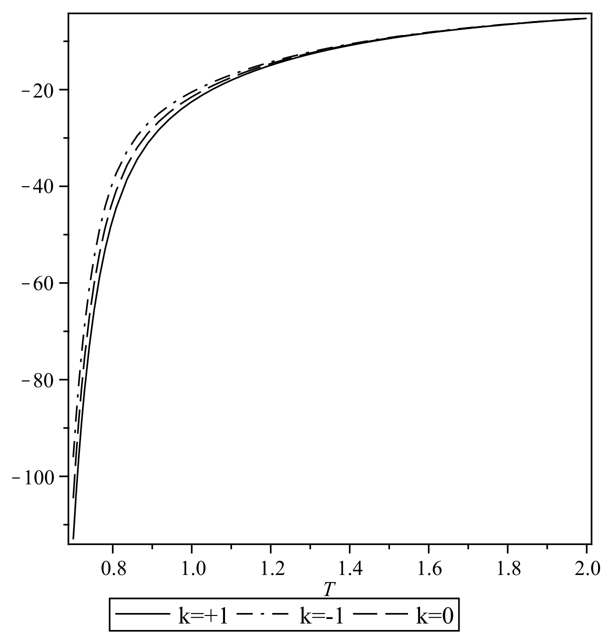

Fig. 4 The plot of p_D vs. t for $\rho_0=1$, $n=3$, $\omega_m=0.5$ in non-interacting two-fluid model

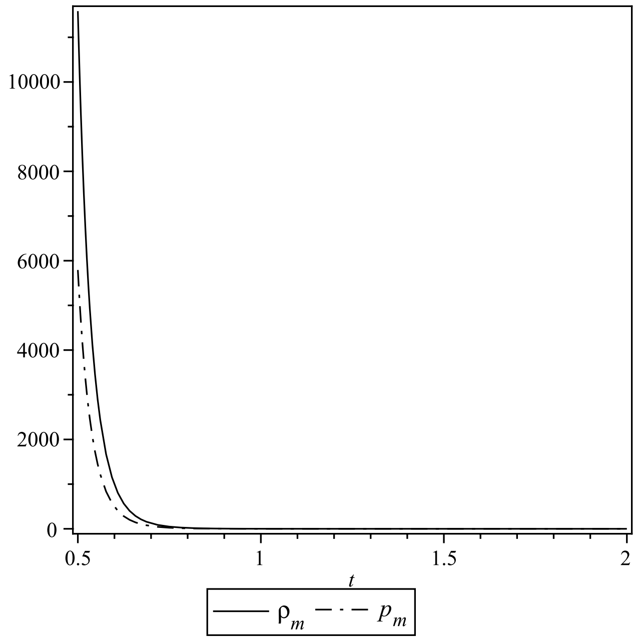

Fig. 5 The plot of ρ_m and p_m vs. t for $\rho_0 = 1$, $n = 3$, $\omega_m = 0.5$ in non-interacting two-fluid model

A convenient method to describe models close to Λ CDM is based on the cosmic jerk parameter j, a dimensionless third derivative of the scale factor with respect to the cosmic time (Chiba and Nakamura 1998; Sahni 2002; Blandford et al. 2004; Visser 2004, 2005). A deceleration-to-acceleration transition occurs for models with a positive value of j_0 and negative q_0. Flat Λ CDM models have a constant jerk $j = 1$. The jerk parameter in cosmology is defined as the dimensionless third derivative of the scale factor with respect to cosmic time

$$j(t) = \frac{1}{H^3}\frac{\dddot{a}}{a} \tag{23}$$

and in terms of the scale factor to cosmic time

$$j(t) = \frac{(a^2H^2)''}{2H^2}, \tag{24}$$

where the 'dots' and 'primes' denote derivatives with respect to cosmic time and scale factor, respectively. The jerk parameter appears in the fourth term of a Taylor expansion of the scale factor around a_0

$$\frac{a(t)}{a_0} = 1 + H_0(t-t_0) - \frac{1}{2}q_0H_0^2(t-t_0)^2 + \frac{1}{6}j_0H_0^3(t-t_0)^3 + O[(t-t_0)^4], \tag{25}$$

where the subscript 0 shows the present value. One can rewrite (23) as

$$j(t) = q + 2q^2 - \frac{\dot{q}}{H}. \tag{26}$$

Equations (22) and (26) reduce to

$$j(t) = \frac{(n-1)(n-2)}{n^2}. \tag{27}$$

This value is overlap with the value $j \simeq 2.16$ obtained from the combination of three kinematical data sets: the gold sample of type Ia supernovae (Riess et al. 2004), the SNIa data from the SNLS project (Astier et al. 2006), and the X-ray galaxy cluster distance measurements (Rapetti et al. 2007) for $n \simeq 0.55$.

4 Interacting two-fluid model

In this section we consider the interaction between dark and barotropic fluids. For this purpose we can write the continuity equations for dark fluid and barotropic fluids as

$$\dot{\rho}_m + 3\frac{\dot{a}}{a}(\rho_m + p_m) = Q, \tag{28}$$

and

$$\dot{\rho}_D + 3\frac{\dot{a}}{a}(\rho_D + p_D) = -Q. \tag{29}$$

The quantity Q expresses the interaction between the dark components. Since we are interested in an energy transfer from the dark energy to dark matter, we consider $Q > 0$. $Q > 0$, ensures that the second law of thermodynamics is fulfilled (Pavon and Wang 2009). Here we emphasize that the continuity (28) and (29) imply that the interaction term (Q) should be proportional to a quantity with units of inverse of time i.e. $Q \propto \frac{1}{t}$. Therefor, a first and natural candidate can be the Hubble factor H multiplied with the energy density. Following Amendola et al. (2007) and Guo et al. (2007), we consider

$$Q = 3H\sigma\rho_m, \tag{30}$$

where σ is a coupling constant. Using (30) in (28) and after integrating, we obtain

$$\rho_m = \rho_0 a^{-3(1+\omega_m-\sigma)}. \tag{31}$$

By using (31) in (3) and (4), we again obtain the ρ_D and p_D in term of scale factor $a(t)$.

$$\rho_D = 3\left(\frac{\dot{a}^2}{a^2} + \frac{k}{a^2}\right) - \rho_0 a^{-3(1+\omega_m-\sigma)}, \tag{32}$$

and

$$p_D = -\left(2\frac{\ddot{a}}{a} + \frac{\dot{a}^2}{a^2} + \frac{k}{a^2}\right) - \rho_0(\omega_m-\sigma)a^{-3(1+\omega_m-\sigma)}, \tag{33}$$

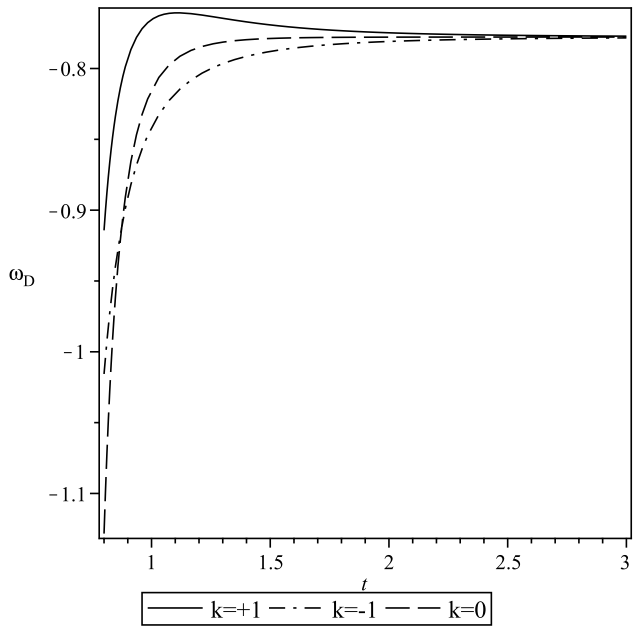

Fig. 6 The plot of EoS parameter vs. t for $\rho_0 = 1$, $\omega_m = 0.5$, $n = 3$, $\sigma = 0.3$ in interacting two-fluid model

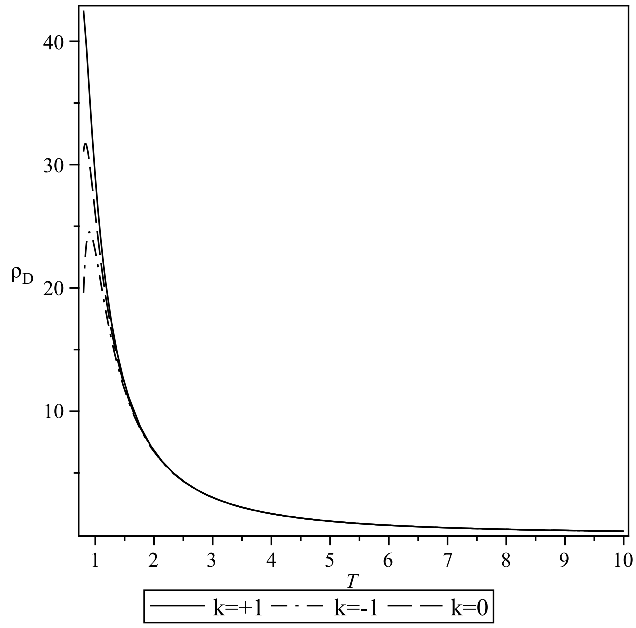

Fig. 7 The plot of ρ_D vs. t for $\rho_0 = 1$, $n = 3$, $\omega_m = 0.5$, $\sigma_m = 0.3$ in interacting two-fluid model

respectively. Putting the value of $a(t)$ from (13) in (32) and (33), we obtain

$$\rho_D = \frac{3n^2}{(t-t_0)^2} + \frac{3k}{(t-t_0)^{2n}} - \rho_0 (t-t_0)^{-3n(1+\omega_m-\sigma)}, \quad (34)$$

and

$$p_D = -\left[\frac{n(3n-2)}{(t-t_0)^2} + \frac{k}{(t-t_0)^{2n}} + \rho_0(\omega_m - \sigma)(t-t_0)^{-3n(1+\omega_m-\sigma)}\right], \quad (35)$$

respectively. Using (34) and (35) in (7), we can find the EoS parameter of dark field as

$$\omega_D = -\left[\frac{\frac{n(3n-2)}{(t-t_0)^2} + \frac{k}{(t-t_0)^{2n}} + \rho_0(\omega_m - \sigma)(t-t_0)^{-3n(1+\omega_m-\sigma)}}{\frac{3n^2}{(t-t_0)^2} + \frac{3k}{(t-t_0)^{2n}} - \rho_0(t-t_0)^{-3n(1+\omega_m-\sigma)}}\right]. \quad (36)$$

The behavior of EoS for dark energy in term of cosmic time t is shown in Fig. 6. It is observed that for open, close and flat universes, the EoS parameter is an increasing function of time, the rapidity of its increase at the early stage depends on the type the universes, while later on it tends to the same constant value independent to it. It is important to mention here that in this case only open and flat universes cross the phantom region.

Figure 7 plots the graph ρ_D versus t. Here we observe that ρ_D decreases as time increases in all the three open, close and flat universes. The pressure for DE p_D versus t is depicted in Fig. 8. It is observed that p_D is always negative in open, close and flat universes as aspected.

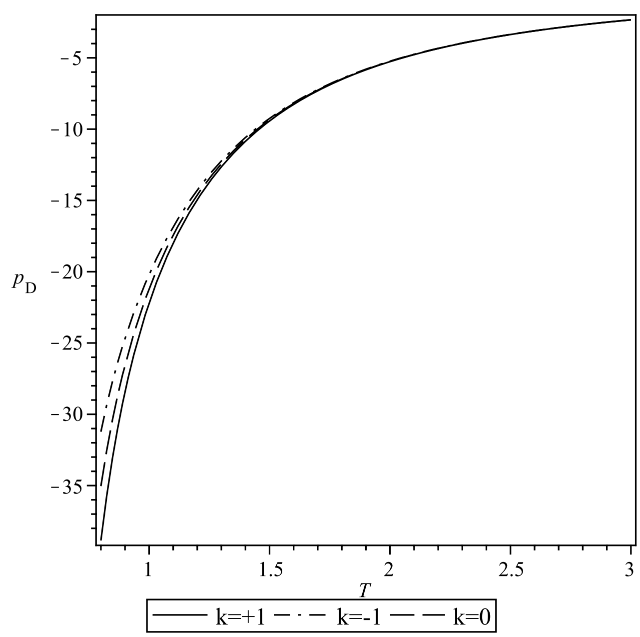

Fig. 8 The plot of p_D vs. t for $\rho_0 = 1$, $n = 3$, $\omega_m = 0.5$, $\sigma_m = 0.3$ in interacting two-fluid model

The expressions for the matter-energy density Ω_m and dark-energy density Ω_D are given by

$$\Omega_m = \frac{\rho_m}{3H^2} = \frac{\rho_0}{3n^2}(t-t_0)^{-3n(1+\omega_m-\sigma)}, \quad (37)$$

and

$$\Omega_D = \frac{\rho_D}{3H^2} = 1 + \frac{k}{n^2(t-t_0)^{2(n-1)}} - \frac{\rho_0}{3n^2}(t-t_0)^{-3n(1+\omega_m-\sigma)}, \tag{38}$$

respectively. From (37) and (38), we obtain

$$\Omega = \Omega_m + \Omega_D = 1 + \frac{k}{n^2(t-t_0)^{2(n-1)}}, \tag{39}$$

which is the same as (19). Therefore, we observe that in interacting case the density parameter has the same properties as in non-interacting case. The expressions for deceleration parameter and jerk parameter are also same as in the case of non-interacting case.

Studying the interaction between the dark energy and ordinary matter will open a possibility of detecting the dark energy. It should be pointed out that evidence was recently provided by the Abell Cluster A586 in support of the interaction between dark energy and dark matter (Bertolami et al. 2007; Delliou et al. 2007). It is observed that for open, close and flat universe, the EoS parameter is an increasing function of time, the rapidity of its increase at the early stage depends on the type the universes, while later on it tends to the same constant value independent to it. It is important to mention here that in this case only open and flat universes cross the phantom region.

5 Concluding remarks

In conclusion, we have studied the system of two-fluid scenario within the scope of a spatially flat and isotropic FRW model. The role of two fluid either minimally or directly coupled in the evolution of the dark energy parameter has been investigated by considering a power law function of time which yields a constant deceleration parameter. It is observed that in non-interacting case all the three open, close and flat universes cross the phantom region whereas in interacting case only open and flat universes cross phantom region.

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