The dark energy cosmology with the equation of state $w = \text{constant}$ is considered in this paper. The $\Omega_{DE} - \Omega_M$ plane has been used to study the present state and expansion history of the universe. Through the mathematical analysis, we give the theoretical constraint of cosmological parameters. Together with some observations such as the transition redshift from deceleration to acceleration, more precise constraint on cosmological parameters can be acquired.

Subject headings: cosmological parameters—cosmology:theory—dark energy—observations

1. Introduction

One of the greatest challenges in modern cosmology is understanding the nature of the observed evolution status of the universe in late-time phase. The type Ia supernovae (SNe Ia) searches (Riess et al. 1998; Perlmutter et al. 1999), the cosmic microwave background (CMB) results from balloon and ground experiments (Miller et al. 1999; de Bernardis et al. 2000; Hanany et al. 2000; Halverson et al. 2002; Mason et al. 2003; Benoît et al. 2003) and recent WMAP (Spergel et al. 2003) and recent WMAP (Spergel et al. 2003) observation all suggest that the universe is spatially flat and undergoing a phase of accelerating at the present time due to the current domination of some sort of negative-pressure dark energy (DE). The dark energy is usually characterized by a parameter of an equation-of-state (hereafter, EOS) $w \equiv p/\rho$, the ratio of the spatially-homogeneous dark-energy pressure $p$ to its energy density $\rho$. The cosmological constant (Weinberg 1989; Carroll et al. 1992; Ostriker & Steinhardt 1995) of order $(10^{-3}\text{eV})^4$, the EOS of which $w = -1$, is the simplest candidate for dark energy. However, it is 120 orders of magnitude smaller than the naive expectations from quantum field theory. Another widely explored possibility is quintessence (Ratra & Peebles
1988; Coble et al. 1997; Caldwell et al. 1998), which is described in terms of a cosmic scalar field $\phi$. Thus in such models, the EOS takes $-1 < w < -1/3$, and the dark-energy density decreases with scale factor $a(t)$ as $\rho \propto a^{-3(1+w)}$.

The $\Omega_{DE} - \Omega_M$ plane is one of the most fundamental diagrams in modern observational cosmology, which has been used to study the present state and expansion history of the universe. To study the cosmological dynamics of the universe for different scenarios the phase plane analysis is used. In this paper, we focus on the case of EOS $w = constant$ for simplicity. Three choices of $w$ are taken to be examples of our analysis, however, this analysis method can be appropriate for arbitrary $w$. The case of $w = -1$, which represents the dark energy is a constant independent of cosmic time (the cosmological constant), is the simplest choice for dark energy. Furthermore, it was strongly supported by SNe Ia (Riess et al. 2004) and CMB (Spergel et al. 2003) observations. Another candidate for dark energy is the cosmic topological defect (Peebles & Ratra 2003) such as cosmic string (Vilenkin & Shellard 1994) and domain wall (Battye et al. 1999), and so on. The EOS of topological defect is $w = -n/3$, where $n$ is the dimension of defect. $n = 1$ (accordingly $w = -1/3$) corresponds to cosmic string and $n = 2$ ($w = -2/3$) corresponds to domain wall respectively. In addition, these choices of $w$ are easy to be calculated analytically.

This paper is organized as follows: in Sec. 2 we discuss the restrictions which can be set on this cosmological model from the astronomical observations, and in Sec. 3 the $\Omega_{DE} - \Omega_M$ plane of the three cases ($w = -1, -1/3$ and $-2/3$) is discussed in detail. We study the transit redshift from deceleration to acceleration in the $\Omega_{DE} - \Omega_M$ plane in Sec. 4. The discussion of the results and their further possible generalization is presented in Sec. 5.

### 2. The Equation of State for Dark Energy

For most purpose, we consider a general dark energy EOS $w(z)$ which varies with the cosmic time $t$ or redshift $z$

$$w(z) = \frac{p_{DE}(z)}{\rho_{DE}(z)}, \quad (1)$$

where $p_{DE}(z)$ and $\rho_{DE}(z)$ are the time-dependent pressure and energy density respectively and redshift $z$ is defined by scale factor $a$, $1 + z = a_0/a$. Using the conservation of energy, we can express the energy density of dark energy by

$$f_{DE}(z) = \frac{\rho_{DE}(z)}{\rho_{DE0}} = \exp \left[ \int_0^z 3(1 + w_{DE}(z))d \ln(1 + z) \right]. \quad (2)$$
Thus Friedmann equation neglecting cosmic radiation can be expressed as

\[ E^2(z) = \frac{H^2(z)}{H_0^2} = \Omega_M(1+z)^3 + \Omega_{DE} f_{DE}(z) + \Omega_k (1+z)^2, \tag{3} \]

where \( \Omega_M, \Omega_{DE} \) and \( \Omega_k \) are respectively density parameters at the present epoch \( t_0 \). More generally, we can rewrite Eq.(3) in terms of cosmological density parameters at redshift \( z \)

\[ \Omega_M^z + \Omega_{DE}^z + \Omega_k^z = 1, \tag{4} \]

where

\[
\begin{aligned}
\Omega_M^z &= \frac{\rho_M}{\rho_c} = \frac{\rho_{M0}(1+z)^3}{\rho_{c0}E^2(z)} = \frac{\Omega_M(1+z)^3}{E^2(z)}, \\
\Omega_{DE}^z &= \frac{\rho_{DE}}{\rho_c} = \frac{\rho_{DE0}f_{DE}(z)}{\rho_{c0}E^2(z)} = \frac{\Omega_{DE}f_{DE}(z)}{E^2(z)}, \\
\Omega_k^z &= -\frac{k^2}{a^2(z)H^2(z)} = \frac{\Omega_k(1+z)^2}{E(z)^2},
\end{aligned} \tag{5} \]

and the critical density at redshift \( z \) is

\[ \rho_c = \frac{3H^2}{8\pi G} = \frac{3H_0^2}{8\pi G}E^2(z) = \rho_{c0}E^2(z). \tag{6} \]

If \( w_{DE}(z) = w \) (constant) is independent of time, the expression for \( \rho_{DE}(z) \) above becomes

\[ f_{DE}(z) = \frac{\rho_{DE}(z)}{\rho_{DE0}} = (1+z)^{3(1+w)} \propto a^{-3(1+w)}, \tag{7} \]

and the expression of \( E(z) \) reduces to

\[ E(z) = \sqrt{\Omega_M(1+z)^3 + \Omega_{DE}(1+z)^3(1+w) + \Omega_k (1+z)^2}. \tag{8} \]

Throughout this paper, we just consider constant EOS \( w \) rather the variation of its \( w(t) \). At the present epoch, Eq.(4) satisfies \( \Omega_M + \Omega_{DE} + \Omega_k = 1 \). For spatially flat universe, \( \Omega_k = 0 \), i.e. \( \Omega_M + \Omega_{DE} = 1 \), then

\[ \Omega_T^z = \Omega_M^z + \Omega_{DE}^z = \frac{\Omega_M(1+z)^3}{E^2(z)} + \frac{\Omega_{DE}(1+z)^3(1+w)}{E^2(z)} = 1, \tag{9} \]

which means \( \Omega_T^z \) will equal unit at any redshift \( z \) if only the universe is spatially flat today. Fig.1 draw the cosmological density parameters \( \Omega^z \) as a function of redshift \( z \) in various spatially flat cosmologies. With the expansion of the universe from the Big Bang (redshift \( z = \infty \)) to the future (\( z = -1 \)) theoretically, matter density \( \Omega_M^z \) drops to zero from unit, while dark energy density \( \Omega_{DE}^z \) reaches unit from zero. The universe start from Einstein-de
Fig. 1.— The evolution of cosmological density parameters $\Omega^z_{M, DE, k, T}$ as a function of redshift $z$, where we have assumed a spatially flat concordant cosmological model: $\Omega_M = 0.3$ and $\Omega_{DE} = 0.7$ with $w = -1$ and $\Omega_k = 0$. The solid and dashed lines denote the evolution of $\Omega^z_M$ and $\Omega^z_{DE}$, while the two horizontal straight lines correspond to that of $\Omega^z_T$ and $\Omega^z_k$, respectively. From left to right for $z > 0$ and from right to left for $z < 0$, the solid lines representing $\Omega^z_M$ and the dashed lines representing $\Omega^z_{DE}$ correspond to the cases of $w = -3/2, -1, -2/3, -1/2$ and $-1/3$.

Sitter model and end in a de-Sitter phase. This point can also be demonstrated theoretically by taking the limit of Eq.(5)

$$\lim_{z \to \infty} \Omega^z_M = \lim_{z \to \infty} \frac{\Omega_M(1 + z)^3}{E^2(z)} = 1, \quad \lim_{z \to -1} \Omega^z_M = 0;$$

$$\lim_{z \to \infty} \Omega^z_{DE} = \lim_{z \to \infty} \frac{\Omega_{DE}\exp\left[3 \int^z_0 (1 + w(z))d \ln(1 + z)\right]}{E^2(z)} = 0, \quad \lim_{z \to -1} \Omega^z_{DE} = 1. \quad (10)$$
3. The $\Omega_{DE} - \Omega_M$ Plane and the Expansion History of the Universe

Using Eq.(5), we can relate the density parameters $\Omega^z_{M,DE,k}$ at $z$ and their current ones $\Omega_{M,DE,k}$ by

$$\frac{(\Omega^z_M + \Omega^z_{DE} - 1)^3}{(\Omega^z_M)^{(1+3w)/w}(\Omega^z_{DE})^{-1/w}} = \frac{(\Omega_M + \Omega_{DE} - 1)^3}{\Omega_M^{(1+3w)/w} \Omega_{DE}^{-1/w}} = C. \quad (11)$$

Given the value of the constant $C$, one can represent the specific cosmological models by the second term and the expansion history of the universe by the first term in Eq.(11) in the $\Omega_{DE} - \Omega_M$ plane respectively. This leads to the identity of the the $\Omega_{DE} - \Omega_M$ plane and the expansion history of the universe in the $\Omega_{DE} - \Omega_M$ plane.

The universe can be roughly divided into three types: open, flat and closed. In the absence of the exotic dark energy, the fate of the universe are easily to be understood. At the presence of dark energy, the situation becomes more complicated. Especially, the recollapse of the universe can exist in some types of cosmological models. From the definition of expansion rate of the universe, Eq.(3), one can guarantee the existence of recollapse by the criterion $\dot{a}(t) = 0$ at some moment $t$

$$\frac{H^2(z)}{H_0^2} = \left(\frac{\dot{a}/a}{H_0}\right)^2 = E^2(z) = \Omega_M(1 + z)^3 + \Omega_{DE}f_{DE}(z) + \Omega_k(1 + z)^2 = 0. \quad (12)$$

Setting $x = a/a_0 = 1/(1 + z)$, we can see that when $z$ varies from $+\infty$ to $-1$, $x$ varies from 0 to $+\infty$. Defining a function

$$F(x) = \Omega_{DE}x^{-3w} + \Omega_kx + \Omega_M, \quad (13)$$

we can easily find that $E^2(z) \geq 0 \iff F(x) \geq 0$, and if only there exists a positive root to $F(x)$, the universe can recollapse at some time $a(t)$.

3.1. The Case of $w = -1$

For the case of cosmological constant, $w = -1$, we have

$$\frac{(\Omega^z_M + \Omega^z_{DE} - 1)^3}{(\Omega^z_M)^2 \Omega^z_{DE}} = \frac{(\Omega_M + \Omega_{DE} - 1)^3}{\Omega_M^2 \Omega_{DE}} = C, \quad (14)$$

for $\Omega_{DE} - \Omega_M$ plane and the expansion trajectory of the universe in the $\Omega_{DE} - \Omega_M$ plane, and

$$F(x) = \Omega_{DE}x^3 + \Omega_kx + \Omega_M. \quad (15)$$

Given the value of $C$, one can follow the expansion trajectory of the universe in terms of the density parameters $\Omega^z$ at any redshift $z$, which, essentially, is identical to the $\Omega_{DE} - \Omega_M$
plane that represents the location of specific cosmological models in terms of current density parameters $\Omega$. Parameter $C$ cannot be arbitrary for the constrain condition $F(x) \geq 0$ (otherwise, $E^2(z) = H^2/H_0^2 < 0$, it is impossible). So we get $\Omega_{DE} \geq 0$. Below we just consider the situation of $\Omega_{DE} > 0$, the case of $\Omega_{DE} = 0$ is just the limit of $C \to -\infty$ (see below). Taking the derivation of $F(x)$, we have

$$F'(x) = 3\Omega_{DE}x^2 + \Omega_k. \quad (16)$$

For the cases $\Omega_k > 0$ ($k = -1$) and $\Omega_k = 0$ ($k = 0$), which correspond to $C < 0$ and $C = 0$ respectively, $F'(x) > 0$, so $F(x) > F(0) = \Omega_M > 0$ will be satisfied for all values of $x$. There is something different for the case $\Omega_k < 0$ ($k = 1$) which corresponds to $C > 0$. There is a positive root $x = x_0 = \sqrt{-\Omega_k/3\Omega_{DE}}$ for equation $F'(x) = 0$. And we can further get that $x_0$ is the minimum point of $F(x)$ for $F''(x_0) > 0$. If only $F(x_0) \geq 0$, $F(x) \geq 0$. So this condition leads to $C \leq 27/4$. To sum up, the value of $C$ can’t be arbitrary. There is a basic constraint from the standard cosmology. For the case of $w = -1$, $C$ has to be in the range $(-\infty, 27/4]$. Only when $C = 27/4$, $F(x_0) = 0$, that is to say $F(x)$ has a positive root $x = x_0$, the universe can recollapse at some time; when $C < 27/4$, the universe will expand forever; and when $C > 27/4$, the universe is impossible to exist as a physical one, or to say it is not a Big Bang universe.

These results are displayed in Fig.2. The permitted region is the interior of the line labelled $C = 27/4$.

### 3.2. The Case of $w = -1/3$

In this case, Eq.(11) describing the $\Omega_{DE} - \Omega_M$ plane and the expansion trajectory of the universe reduces to

$$\frac{\Omega_M^2 + \Omega_{DE}^2 - 1}{\Omega_{DE}^2} = \frac{\Omega_M + \Omega_{DE} - 1}{\Omega_{DE}} = \sqrt{C}, \quad (17)$$

and the function $F(x)$ becomes

$$F(x) = (\Omega_{DE} + \Omega_k)x + \Omega_M, \quad (18)$$

which can be further written as

$$F(x) = (1 - \Omega_M)x + \Omega_M. \quad (19)$$

From the condition $F(x) \geq 0$, we get $0 < \Omega_M \leq 1$ (it can be easily understood that $\Omega_M > 0$ originates from the fact that the matter density can’t be negative). According to
Eq. (17), we have $0 < \Omega_M = (\sqrt[3]{C} - 1)\Omega_{DE} + 1 \leq 1$, so

$$
\begin{align*}
C &= -\infty, & \text{for } \Omega_{DE} > 0 \\
C &= \pm \infty, & \text{for } \Omega_{DE} = 0 \\
1 \leq C < +\infty, & \text{for } \Omega_{DE} < 0
\end{align*}
$$

(20)

These results are displayed in Fig. 3. And there isn’t a positive root for function $F(x)$, so this kind of universe will expand forever.

### 3.3. The Case of $w = -2/3$

In this case, Eq. (11) reduces to

$$
\frac{\Omega_M + \Omega_{DE} - 1}{\sqrt{\Omega_M \sqrt{\Omega_{DE}}}} = \frac{\Omega_M + \Omega_{DE} - 1}{\sqrt{\Omega_M \sqrt{\Omega_{DE}}}} = \sqrt[3]{C},
$$

(21)
Fig. 3.— The same as Fig. 2 but for the case of $w = -1/3$. The permitted region of $\Omega_{DE}$ and $\Omega_M$ is between the two vertical line.

and the function $F(x)$ becomes

$$F(x) = \Omega_{DE} x^2 + \Omega_k x + \Omega_M.$$  \hfill (22)

$F(x) \geq 0$ needs $\Omega_{DE} \geq 0$ (also we just consider $\Omega_{DE} > 0$). The same as done in the case $w = -1$, we study the derivation of $F(x)$

$$F'(x) = 2\Omega_{DE} x + \Omega_k.$$  \hfill (23)

For the cases $\Omega_k > 0 (k = 1)$ and $\Omega_k = 0 (k = 0)$, which correspond to $C < 0$ and $C = 0$ respectively, $F''(x) > 0$, so $F(x) > F(0) = \Omega_M > 0$ will be satisfied for all values of $x$. For the case of $\Omega_k < 0 (k = 1)$ which corresponds to $C > 0$, there is a positive root $x = x_0 = -\Omega_k / 2\Omega_{DE}$ of equation $F'(x) = 0$ and $x_0$ is also the minimum point of $F(x)$ for $F''(x_0) > 0$. From $F(x_0) \geq 0$ we get $C \leq 8$. So $C$ has to be in the range $(-\infty, 8]$. Only when $C = 8$, $F(x)$ has a positive root $x = x_0$, the universe can recollapse at some time; when $C < 8$, the universe will expand forever; and when $C > 8$, the universe is impossible to exist as a physical one.
Fig. 4.— The same as Fig. 2 but for the case of $w = -2/3$. The permitted region is the interior of the line labelled $C = 8$.

It can be shown from Fig. 4 that the expansion history of the universe are very familiar with that of cosmological constant but with the boundary of $C = 8$.

4. The Transition Redshift from Deceleration to Acceleration in the $\Omega_{DE} - \Omega_M$ Plane

The decelerating parameter $q(z)$ is defined by

$$q(z) \equiv \left(\frac{-\ddot{a}}{a}\right)/H^2(z) = \frac{1}{2E^2(z)} \frac{dE^2(z)}{dz}(1 + z) - 1,$$

(24)

the present value $q_0 = q(z = 0)$ of which is called decelerating factor. At the transit redshift $z_T$, the universe reaches $\dot{a}(z_T) = 0$ or $q(z_T) = 0$ and evolves from deceleration to acceleration expansion, thus we can get the relation between density parameters and transition redshift
Fig. 5.— The $\Omega_{DE} - \Omega_M$ plane with the best fit estimate of transition redshift $z_T$ (Riess et al. 2004) for the case of $w = -1$. The curve labelled $C = 27/4$ is the boundary of this model.

$z_T$ in $\Omega_{DE} - \Omega_M$ plane

\[
\Omega_{DE} = \frac{1}{(1 + 3w)(1 + z_T)^3w} \Omega_M, \tag{25}
\]

which leads to

\[
\Omega_{DE} = -\frac{\Omega_M}{(1 + 3w)}, \tag{26}
\]

at $z_T = 0$ or $q_0 = 0$. Clearly, as the transition redshift increases with the decrease of $\Omega_m$. The $\Omega_{DE} - \Omega_M$ plane with the best fit estimate of transition redshift $1 + z_T = 1.46 \pm 0.13$, and together with the theoretical constraints discussed above for $w = -1, -1/3$ and $-2/3$ are shown in Fig.5, 6 and 7 respectively.
5. Conclusion and Discussion

In this paper we examined the dynamical evolution of the universe filled with a dark energy of EOS $w = \text{constant}$. Based on the Big Bang model, we give some theoretical constraints of cosmological parameters of three special cases in the $\Omega_{DE} - \Omega_M$ plane. The physical constrain condition of $E^2(z) \geq 0$ makes the cosmological parameters not be arbitrary. It is shown in the $\Omega_{DE} - \Omega_M$ plane by a limited region rather than all of the plane. Together with the observational results of $z_T$, we can constrain the cosmological parameters more strictly. It is shown in the Figs.5—7 that the observation of $z_T$ is compatible with the model of cases of $w = -1$ and $w = -2/3$ to great extent, but is not consistent with the one of $w = -1/3$. This has also been revealed in work on the supernova measurements (Garnavich et al. 1998; Perlmutter et al. 1999). Apparently, the dark energy model with $w < -1/3$ make a positive contribution to the acceleration of the universe, while the model with $w = -1/3$ has effect on neither the acceleration nor deceleration. In fact, the supernova observation supports an accelerating universe. On the other hand, because there still exists difficulty in
the accurate treatment of the behavior of cosmological defect models partly, these models have not been very thoroughly studied (Spergel & Pen 1997). Thus, due to this motivation we in this paper just make a try to test the cosmic defect models by the properties of $\Omega_{DE} - \Omega_M$ plane, which maybe provides an alternative method to test cosmological models.

In addition, when $-1 < w < -1/3$, it is similar to the case of $w = -2/3$ but is difficult to be studied analytically. From $F(x) \geq 0$ we have a general result $\Omega_{DE} \geq 0$. While $-1/3 < w < 0$, there should be $\Omega_k \geq 0$ generally. There would be some difficulties to get the range of $C$. For an arbitrary value of $w$, one can give the detailed results numerically from Eq.(11) and Eq.(13).

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