Constraints on alternative models to dark energy

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Abstract. The recent observations of type Ia supernova strongly support that the universe is accelerating now and decelerated in the recent past. This may be the evidence of the breakdown of the standard Friedmann equation. We consider a general modified Friedmann equation. Three different models are analyzed in detail. The current supernova data and the Wilkinson microwave anisotropy probe data are used to constrain these models. A detailed analysis of the transition from the deceleration phase to the acceleration phase is also performed.

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1. Introduction

The recent observations of Type Ia supernova indicate that the expansion of the universe is speeding up [1]. Observational results also provide the evidence of a decelerated universe in the recent past [2]. On the other hand, the cosmic background microwave (CMB) observations indicate that the universe is spatially flat as predicted by the inflationary models [3]. A dark energy component with negative pressure behavior which dominates the universe, was proposed to explain a flat and accelerating universe. One simple candidate of dark energy is the cosmological constant. However, there are some problems with the cosmological constant although cold dark matter cosmological constant models are consistent with the current observations. Why is the cosmological constant so small and not zero? Why does the cosmological constant become significant now? The quintessence models avoid some of the problems [4]. There are also other models, like tachyon filed as dark energy [5]. But the property of dark energy is still mysterious. One logical possibility is that the standard Friedmann equation may need to be modified. In this scenario, the universe is dominated by ordinary pressureless matter, but the law of gravity and the standard Friedmann equation are modified. The idea of modifying the law of gravity is not new. The modified Newtonian Dynamics (MOND) was first used to explain the rotation curve in place of dark matter [6,7]. In MOND, the Newtonian gravity $M/r^2$ is replaced with $M/r^2 + \sqrt{M/r}$. Since $M/r^2$ gives the standard Friedmann equation $H^2 \sim \rho$, $M/r^2 + \sqrt{M/r}$ may provide a modified Friedmann equation $H^2 \sim \rho^{2/3} \ln \rho + \rho^{2/3}$ [7]. Recall that the brane cosmology gives a non-standard Friedmann equation $H^2 \sim \rho^{\alpha} \ln \rho + \rho^{\alpha}$ [8,9,10]. Along this line of reasoning, Freese and Lewis recently proposed the Cardassian expansion in which the universe is dominated by the ordinary matter and the Friedmann equation becomes $H^2 \sim \rho + \rho^\alpha$ [11]. The Cardassian model was later generalized to a more general form $H^2 \sim g(\rho)$ [12]. In addition, several authors modified the Friedmann equation as $H^2 + H^\alpha \sim \rho$ motivated by theories with extra dimensions [13,14]. In this paper, we first consider a model which is equivalent to the generalized Chaplygin gas model [15] in terms of dynamical evolution. Then we consider the generalized Cardassian model. At last we consider a model proposed by Dvali, Gabadadze and Porrati (DGP) [13]. We use the ten new supernovae at $z = 0.36 - 0.86$ [16] and the the first year Wilkinson Microwave Anisotropy Probe (WMAP) temperature (TT) and temperature polarization cross correlation (TE) data [17] to constrain these models. We also investigate the transition from the decelerated phase to the accelerated phase.

For a spatially flat, isotropic and homogeneous universe with both an ordinary pressureless dust matter and a minimally coupled scalar field $Q$ sources, the Friedmann equations are

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}(\rho_m + \rho_Q),$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho_m + \rho_Q + 3p_Q),$$

(1)
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\[ \dot{\rho}_Q + 3H(\rho_Q + p_Q) = 0, \]

where dot means derivative with respect to time, \( \rho_m = \rho_{m0}(a_0/a)^3 \) is the matter energy density, a subscript 0 means the value of the variable at present time, \( \rho_Q = \dot{Q}^2/2 + V(Q) \), \( p_Q = \dot{Q}^2/2 - V(Q) \) and \( V(Q) \) is the potential of the quintessence field. The modified Friedmann equations (MFE) for a spatially flat universe are

\[ H^2 = H_0^2g(x), \]
\[ \frac{\ddot{a}}{a} = H_0^2g(x) - \frac{3H_0^2}{2}g'(x) \left( \frac{\rho + p}{\rho} \right), \]
\[ \dot{\rho} + 3H(\rho + p) = 0, \]

where \( x = 8\pi G\rho/3H_0^2 = x_0(1+z)^3 \) during the matter dominated epoch, \( 1+z = a_0/a \) is the redshift parameter, \( g(x) = x + \cdots \) is a general function of \( x \) and \( g'(x) = dg(x)/dx \). From phenomenological point of view, four dimensional gravity is modified so that we get a general function \( g(x) \). Chung and Freese argued that a general \( g(x) \) is possible if our universe as a three brane is embedded in five dimensional spacetime \[12\]. For example, \( g(x) \sim x + x^2 \) in Brane cosmology, \( g(x) \sim x + x^n \) in Cardassian model. On the other hand, we can think the additional terms \( g(x) - x \) as dark energy component. For the Cardassian model, the additional term \( x^n \) can be mapped to a dark energy component with constant equation of state parameter \( \omega_Q = n - 1 \). In general, we get the following relationship between the dark energy equation of state parameter and \( g(x) \)

\[ \omega_Q = \frac{xg'(x) - g(x)}{g(x) - x}. \]

The equivalent dark energy potential can be found from the following equations

\[ \dot{Q}^2 = \rho_m[g'(x) - 1], \]
\[ V(Q) = \frac{3H_0^2}{8\pi G}[g(x) - 0.5x - 0.5xg'(x)]. \]

For instance, if \( g(x) \sim x + x^n \), we find that \( V(Q) \sim [\sinh(AQ + B)]^{2n/(n-1)} \). Note that the universe did not start to accelerate when the other terms in \( g(x) \) started to dominate. The linear density perturbation of this model is given by

\[ \ddot{\delta} + 2H\dot{\delta} = 4\pi G\bar{\rho}\delta[g'(\bar{x}) + 3\bar{x}g''(\bar{x})]. \]

For the matter dominated flat universe, \( \rho = \rho_m \) and \( p = p_m = 0 \). Let \( \Omega_{m0} = 8\pi G\rho_0/3H_0^2 \), then \( x_0 = \Omega_{m0}, \ g(x_0) = 1 \). In general, \( x = \Omega_{m0}(1+z)^3 + \Omega_{r0}(1+z)^4 \), where \( \Omega_{r0} = 8.35 \times 10^{-5} \) is the current radiation component \[18\].

2. Analytical Method

The location of the \( m \)-th peak of the CMB power spectrum is parameterized as \[19\]

\[ l_m = (m - \phi_m)l_A, \]

where the acoustic scale \( l_A \) is

\[ l_A = \frac{\pi \tau_0 - \tau_s}{c_s} \frac{\pi}{\tau_s} = \frac{\pi}{c_s} \int_0^\tau_s \frac{g[\Omega_{m0}(1+z)^3 + \Omega_{r0}(1+z)^4] - 1/2}{dz} \]

\[ \int_0^\infty \frac{g[\Omega_{m0}(1+z)^3 + \Omega_{r0}(1+z)^4] - 1/2}{dz}, \]
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\( c_s = 0.52 \), the conformal time at last scattering \( \tau_{ls} \) and today \( \tau_0 \) are

\[
\tau_{ls} = \int_0^{\tau_{ls}} d\tau = \int_{z_{ls}}^{\infty} \frac{dz}{a_0 H_0 \sqrt{g[\Omega_m0(1+z)^3 + \Omega_r0(1+z)^4]}}.
\]

\[
\tau_0 = \int_0^{\tau_0} d\tau = \int_{z_0}^{\infty} \frac{dz}{a_0 H_0 \sqrt{g[\Omega_m0(1+z)^3 + \Omega_r0(1+z)^4]}}.
\]

The recent WMAP results give the positions of the first two acoustic peaks as \( l_{p1} = 220.1 \pm 0.8 \) and \( l_{p2} = 546 \pm 10 \), respectively \[17\]. The third peak is given by the BOOMERanG measurements as \( l_{p3} = 845 \pm 12 \) \[20\]. We first use equations (11)-(14) with \( \phi_1 = 0.3074, \phi_2 = 0.2819 \) and \( \phi_3 = 0.341 \) to constrain the models considered below, then we use the full 1350 WMAP TT and TE data \[17\] by a modified CMBFAST code version 4.5.1 \[21\] to constrain the parameters. For the fit to full WMAP data, a scalar power spectrum with normalization 0.833, spectral index 0.93 and running index slope -0.031 are assumed. Other cosmological parameters are chosen as follows: \( h = 0.71, \Omega_b = 0.044, T_{cmb} = 2.725 \), Helium abundance \( Y_{He} = 0.24 \), Number of massless neutrinos is 3.04 and \( g^* = 10.75 \).

The luminosity distance \( d_L \) is defined as

\[
d_L(z) = a_0(1+z) \int_t^{t_0} \frac{dt'}{a(t')} = \frac{1+z}{H_0} \int_0^{z} \frac{du}{\sqrt{g[\Omega_m0(1+u)^3]}}.
\]

The apparent magnitude redshift relation becomes

\[
m(z) = M + 5 \log_{10} d_L(z) + 25 = \mathcal{M} + 5 \log_{10} D_L(z)
\]

\[
= \mathcal{M} + 5 \log_{10} \left[ (1+z) \int_0^{z} \frac{du}{\sqrt{g[\Omega_m0(1+u)^3]}} \right],
\]

where \( D_L(z) = H_0 d_L(z) \), \( M \) is the absolute magnitude and \( \mathcal{M} = M - 5 \log_{10} H_0 + 25 \). The nuisance parameter \( \mathcal{M} \) can be determined from the low redshift limit at where \( D_L(z) = z \). The parameters in the models are determined by minimizing

\[
\chi^2 = \sum_i \frac{(m_{\text{obs}}(z_i) - m(z_i))^2}{\sigma_i^2},
\]

where \( \sigma_i \) is the total uncertainty in the observation. We use equations (13) and (16) to fit the ten new supernova data with host galaxy correction \[16\]. The nuisance parameter \( \mathcal{M} \) is marginalized when we fit the supernova data.

The transition from deceleration to acceleration happens when the deceleration parameter \( q = -\ddot{a}/aH^2 = 0 \). From equations (4) and (5), we have

\[
g[\Omega_m0(1+z_{q=0})^3] = \frac{3}{2} \Omega_m0(1+z_{q=0})^3g'[\Omega_m0(1+z_{q=0})^3],
\]

\[
q_0 = \frac{3}{2} \Omega_m0g'(\Omega_m0) - 1.
\]
3. Chaplygin Gas Model

In the framework of MFE, the generalized Chaplygin gas model $p_c = -A/\rho_\alpha^\beta$ becomes

$$g(x) = x + \Omega_0(A_s + (1 - A_s)(x/\Omega_{m0})^\beta)^{1/\beta},$$

where $\Omega_0 = 1 - \Omega_{m0} - \Omega_{r0}$, $\beta = 1 + \alpha$ and $A_s = (8\pi G/3H_0^2\Omega_0)^\beta A$. To recover the standard Friedmann equation at early times, we need $A_s \sim 1$. When $A_s = 1$, the model becomes a standard $\Lambda$-model. Now we have

$$\int_0^2 \frac{du}{\sqrt{g[\Omega_{m0}(1 + u)^3 + \Omega_{r0}(1 + u)^4]}} = \int_0^2 \frac{du}{\sqrt{f(u) + \Omega_0(A_s + (1 - A_s)(1 + u)^3 + \Omega_{r0}(1 + u)^4/\Omega_{m0})^{1/\beta}}},$$

where $f(u) = \Omega_{m0}(1 + u)^3 + \Omega_{r0}(1 + u)^4$. Since $g'(x) = 1 + \Omega_0(1 - A_s)[A_s + (1 - A_s)(x/\Omega_{m0})^\beta]^{1/\beta - 1}(x/\Omega_{m0})^\beta$, together with equations (18) and (19), we have

$$\frac{\Omega_{m0}}{2\Omega_0}(1 + z_{q=0})^3[A_s + (1 - A_s)(1 + z_{q=0})^{3\beta}]^{1-1/\beta} = A_s - \frac{1}{2}(1 - A_s)(1 + z_{q=0})^{3\beta},$$

$$q_0 = \frac{1}{2} - \frac{3}{2}A_s(1 - \Omega_{m0}).$$

The first three peaks in CMB power spectrum favor a cosmological constant model with $A_s = 1$ or $\beta = 1$. The best fit to the WMAP TT and TE data is $\Omega_{m0} = 0.26$, $A_s = 0.999$ and $\beta = 1.43$ with $\chi^2 = 1448.3$. The ten supernova data also favor a cosmological constant model with $A_s = 1$ or $\beta = 1$. By using the best fit parameters to WMAP data, we get $z_{q=0} = 0.78$ and $q_0 = -0.61$. Because $A_s = 0.999$, so $g(x) \approx x$ at early times. The best fit result to the supernova data is shown in figure 11 and the WMAP TT power spectrum with the best fit parameters is plotted in figure 2.

4. Cardassian Model

We take the generalized Cardassian model

$$g(x) = x[1 + Bx^{\alpha(n-1)}]^{1/\alpha},$$

where $B = (\Omega_{m0}^{-n-1} - 1)/\Omega_{m0}^{\alpha(n-1)}$, $\alpha > 0$ and $n < 1 - 1/(1 - \Omega_{m0}^\alpha)$. At early times, $g(x) \sim x$, so the standard cosmology is recovered. When $n = 0$, $g(x) = B^{1/\alpha}(1 + x^{\alpha}/B)^{1/\alpha}$. For the special case $\alpha = 1$ and $n = 0$, $g(x) = x + B$ which is the standard cosmology with a cosmological constant. If we take $\alpha = 1$ and $n = 1/2$, then we have $g(x) = x + B\sqrt{x}$. If we think the generalized Cardassian model as ordinary Friedmann universe composed of matter and dark energy, we can identify the following relationship for the parameters in the Cardassian and quintessence models

$$\omega_{Q0} = \frac{(n - 1)(1 - \Omega_{m0}^\alpha)}{1 - \Omega_{m0}^\alpha}. $$
The generalized Cardassian model gives

\[ g'(x) = [1 + Bx^{\alpha(n-1)}]^{1/\alpha} + (n - 1)Bx^{\alpha(n-1)}[1 + Bx^{\alpha(n-1)}]^{1/\alpha-1}, \quad (23) \]

\[ \int_0^z \frac{du}{\sqrt{g[\Omega_{m0}(1 + u)^3 + \Omega_{r0}(1 + u)^4]}} \]

\[ = \int_0^z \{f(u)[1 + (\Omega_{m0}^\alpha - 1)[(1 + u)^3 + \Omega_{r0}(1 + u)^4/\Omega_{m0}^\alpha(n-1)]^{1/\alpha}]^{1/2}. \quad (24) \]

Combining equation (23) with equations (18) and (19), we get

\[ 1 + z_{q=0} = [(\Omega_{m0}^\alpha - 1)(2 - 3n)]^{1/3o(1-n)}, \quad (25) \]

\[ q_0 = \frac{1}{2} + \frac{3}{2}(n - 1)(1 - \Omega_{m0}^\alpha). \quad (26) \]

The best fit parameters to the first three peaks in CMB power spectrum are: \( \Omega_{m0} = 0.28 \), \( n = -0.032 \) and \( \alpha = 0.5 \) for the generalized Cardassian model and \( \Omega_{m0} = 0.26 \) and \( n = -0.12 \) for the Cardassian model. For the Cardassian model \( \alpha = 1 \), the best fit parameters to the full WMAP TT and TE data are \( \Omega_{m0} = 0.25 \) and \( n = 0.02 \) with \( \chi^2 = 1461.0 \). The best fit parameters to the ten supernovae data are: \( \Omega_{m0} \sim 0, n = 0.51 \) and \( \chi^2 = 6.66 \). For the generalized Cardassian model, the best fit parameters to the ten supernovae data are: \( \Omega_{m0} \sim 0, n = 0.51, \alpha = 0.54 \) and \( \chi^2 = 6.66 \). In fact, the data
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is not sensitive to \( n \) and \( \alpha \). We get almost the same value of \( \chi^2 \) with different \( \alpha \) and \( n \). So the supernova sample is too sparse to determine the parameters in generalized Cardassian model. By using \( \Omega_{m0} = 0.25 \) and \( n = 0.02 \), we get \( q_0 = -0.6 \), \( z_{q=0} = 0.82 \) and \( \omega_{Q0} = -0.98 \). The best fit curve to the supernova data is shown in figure \( 1 \). The CMB TT power spectrum with the best fit Cardassian parameters is drawn in figure \( 2 \).

5. DGP Model

The model is \( g(x) = [a + \sqrt{a^2 + x}]^2 \) \( \text{[13]} \), where \( a = (1 - \Omega_{m0})/2 \). At high redshift, \( g(x) \sim x \). So the standard cosmology is also recovered in the early times. The conformal time is

\[
\int_0^z \frac{du}{\sqrt{g[\Omega_{m0}(1 + u)^3 + \Omega_{r0}(1 + u)^4]}} = \int_0^z \frac{du}{a + \sqrt{a^2 + \Omega_{m0}(1 + u)^3 + \Omega_{r0}(1 + u)^4}}.
\]

For this model, we find that \( q_0 \) and the transition redshift \( z_{q=0} \) from decelerated expansion to accelerated expansion are

\[
1 + z_{q=0} = \left[ \frac{2(1 - \Omega_{m0})^2}{\Omega_{m0}} \right]^{1/3},
\]

\[
q_0 = \frac{2\Omega_{m0} - 1}{1 + \Omega_{m0}}.
\]

In this model, we have only one free parameter \( \Omega_{m0} \). The locations of the first three peaks in CMB power spectrum give that \( \Omega_{m0} = 0.179 \). The best fit parameter to the WMAP TT and TE data is \( \Omega_{m0} = 0.174 \) with \( \chi^2 = 1485.6 \). The best fit parameter to the supernova data is \( \Omega_{m0} = [0, 1.0] \) centered at 0.21 with \( \chi^2 = 6.67 \). If we map the additional term in the right hand side of the Friedmann equation to dark energy component, we have \( \omega_{Q0} = -1/(1 + \Omega_{m0}) = -0.83 \), \( q_0 = -0.48 \) and \( z_{q=0} = 0.81 \) if we take \( \Omega_{m0} = 0.21 \). The best fit curve to the supernova data is shown in figure \( 1 \) and the best fit curve to the WMAP data is shown in figure \( 2 \).

6. Discussions

One attractive feature of the generalized Chalygin gas model is that it can be considered as a unified dark matter and dark energy model. In the unified scenario, both the dark energy and dark matter components are modelled by the generalized Chaplygin gas. In this paper, we are interested in modelling the generalized Chaplygin gas as dark energy only. We found the best fit parameters in the generalized Chaplygin gas model are \( \Omega_{m0} = 0.26, A_s = 0.999 \) and \( \beta = 1.43 \). Cunha, Alcaniz and Lima found that \( A_s > 0.73 \) by using the combined x ray data of galaxy clusters and supernova data and taking a prior \( \Omega_{m0} = 0.3 \) \( \text{[15]} \). Amendola et al found that \( 1 \leq \beta < 1.2 \) and \( 0.8 < A_s < 1 \) by using WMAP TT data \( \text{[15]} \). In the context of MFE, the generalized Chaplygin gas model tends to be the \( \Lambda \)-model in order to recover the standard cosmology at early times. Our results show that the generalized Chaplygin gas model is almost the same as the \( \Lambda \)-model. By using the best fit parameter, we get \( z_{q=0} = 0.78 \).
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Figure 2. The Best fit curve to wmap data. The dashed line is for generalized Chaplygin gas model with $\Omega_{m0} = 0.26$, $A_* = 0.999$ and $\beta = 1.43$. The Solid line is for Cardassian model with $\Omega_{m0} = 0.25$ and $n = 0.02$; The dash dotted line is for the DGP model with $\Omega_{m0} = 0.174$.

For the Cardassian model, the WMAP TT and TE data give that $\Omega_{m0} = 0.25$ and $n = 0.02$. The 10 supernova data gives that $\Omega_{m0} \sim 0$ and $n = 0.51$. The error from supernova data fit is also large. Zhu and Fujimoto also found low $\Omega_{m0}$ from supernova data [22]. Sen and Sen found that $0.31 < n < 0.44$ and $0.13 < \Omega_{m0} < 0.23$ from supernova data and peaks in CMB power spectrum, $n \leq 0.3$ from WMAP data [23]. Godlowski and Szydlowski found that $\Omega_{m0} = 0.48^{+0.08}_{-0.13}$ and $n = -0.4^{+0.77}_{-1.24}$, and $\Omega_{m0} = 0.51^{+0.05}_{-0.06}$ and $n = -1.2^{+0.77}_{1.06}$ from different sets of supernova data [24]. Frith found that $0.19 < \Omega_{m0} < 0.26$ and $0.01 < n < 0.24$ from supernova data [25]. In general, different analysis gives different results, but they are still consistent with each other at 99% confidence level. Dev, Alcaniz and Jain found that the best fit to the gravitational lensing effect is $n = 0.76$ and $\alpha = 2.4$ by assuming $\Omega_{m0} = 0.3$ for the generalized Cardassian model [26]. Taking the best fit result to WMAP data, we get $z_{q=0} = 0.82$.

For the DGP model, the best fit parameter to the WMAP TT and TE data is $\Omega_{m0} = 0.174$ and the best fit parameter to the ten supernova data is $\Omega_{m0} = 0.21$. Deffayet et al found that $\Omega_{m0} = 0.18^{+0.07}_{-0.06}$ from supernova observations and $\Omega_{m0} = 0.3$ from CMB constraints [27]. However, the constraint from supernova data and CMB data...
are still consistent with each other at 1σ level. If we take the bigger value \( \Omega_{m0} = 0.21 \), then we get \( z_{q=0} = 0.81 \). Multamaki, Gaztanaga and Manera considered the effects of Cardassian model and DGP model on large scale structure and found that these effects are different from that of Λ-model [28].

Due to the uncertainties in the observational data, it is still difficult to discriminate different dark energy models and alternative models. Wang et al showed that future supernova data such as SNAP ‡ could differentiate various models if \( \Omega_{m0} \) is known with 10% accuracy [29]. On the other hand, if we can determine the dynamical evolution of equation of state parameter of dark energy with high precision using model independent method, then we can discriminate different models. Alam et al showed that future SNAP data will provide important insights on the nature of dark energy at high redshifts [30]. Turner and Riess showed that \( z_{q=0} \sim 0.5 \) [2], Daly and Djorgovski found that \( z_{q=0} > 0.3 \) [31]. In conclusion, the above models are consistent with current observations.

In terms of model building, we can assume a particular scale factor which manifests early deceleration and later acceleration, then find out the form of \( g(x) \). For example, we take \( a(t) = a_0[\sinh(t/t_0)]^\beta/\alpha \), then we find \( g(x) = Ax^{2/3} + B \). This model recovers the standard cosmology when \( \beta = 2/3 \).

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