ABSTRACT
We investigate the viability of the braneworld model with energy exchange between the brane and bulk by using the most recent observational data related to the background evolution. We show that this energy exchange behaves like a source of dark energy and can alter the profile of the cosmic expansion. The new supernova Type Ia (SNIa) Gold sample, Supernova Legacy Survey (SNLS) data, the position of the acoustic peak at the last scattering surface from the Wilkinson Microwave Anisotropy Probe (WMAP) observations and the baryon acoustic oscillation peak found in the Sloan Digital Sky Survey (SDSS) are used to constrain the free parameters of this model. To infer its consistency with the age of the Universe, we compare the age of old cosmological objects with that computed using the best-fitting values for the model parameters. At 68 per cent level of confidence, the combination of Gold sample SNIa, cosmic microwave background (CMB) shift parameter and SDSS data bases provides \( \Omega_m = 0.29^{+0.03}_{-0.02}, \Omega_A = -0.71^{+0.03}_{-0.26} \) and \( \mu = -0.40^{+0.28}_{-0.04} \), hence a spatially flat Universe with \( \Omega_K = 0.00^{+0.04}_{-0.02} \). The same combination with SNLS supernova observation gives \( \Omega_m = 0.27^{+0.02}_{-0.03}, \Omega_A = -0.74^{+0.04}_{-0.02} \) and \( \mu = 0.00^{+0.30}_{-0.30} \) consequently provides a spatially flat Universe \( \Omega_K = -0.01^{+0.04}_{-0.03} \). These results obviously seem to be compatible with the most recent WMAP results indicating a flat Universe.

Key words: methods: numerical – methods: statistical – cosmological parameters – cosmology: observations – cosmology: theory – early Universe.

1 INTRODUCTION
Recent observations of Type Ia supernovae (SNIa) suggest the expansion of the Universe is accelerating (Riess et al. 1998; Perlmutter et al. 1999b; Tonry et al. 2003; Riess et al. 2004). As it is well known, all usual types of matter with positive pressure generate attractive forces, which decelerate the expansion of the Universe. A ‘dark energy’ component with negative pressure was suggested to account for the invisible fuel that drives the current acceleration of the Universe. Although the nature of such dark energy is still speculative, an overwhelming flood of papers has appeared which attempt to describe it by devising a great variety of models (see Weinberg 1989; Armendariz-Picon, Mukhanov & Steinhardt 2000; Sahni & Starobinsky 2000; Bagla, Jassal & Padmanabhan 2003; Lima 2004; Copeland, Sami & Tsujikawa 2006 for recent reviews). Available models of dark energy differ in the value and variation of the equation of state parameter, \( w \), during the evolution of the Universe. Among them are cosmological constant \( \Lambda \), an evolving scalar field (referred to by some as quintessence), the phantom energy, in which the sum of the pressure and energy density is negative, the quintom model, the holographic dark energy, the Chaplygin gas and the Cardassion model. Another approach dealing with this problem is using the modified gravity by changing the Einstein–Hilbert action. Some of models as \( 1/R \) and logarithmic models provide an acceleration for the Universe at the present time (Weinberg 1989; Carroll 2001; Bennett et al. 2003; Padmanabhan 2003; Peebles & Ratra 2003; Peiris et al. 2003; Spergel et al. 2003; Miranda et al. 2001; Rahvar & Movahed 2007; Wetterich 1998; Ratra & Peebles 1988; Frieman et al. 1995; Turner & White 1997; Caldwell, Dave & Steinhardt 1998; Liddle & Scherrer 1998; Zlatev, Wang & Steinhardt 1999; Steinhardt, Wang & Zlatev 1999; Torres 2002; Peebles & Ratra 1998; Caldwell, Kamionkowski & Weinberg 2003; Arbabi-Bidgoli, Movahed & Rahvar 2006; Wang et al. 2000; Perlmutter, Turner & White 1999a; Page et al. 2003; Doran et al. 2001; Doran & Lilley 2002; Caldwell & Doran 2004; Caldwell 2002; Dabrowski, Stachowiak & Szydlowski 2003; Amendola 2000, 2003; Amendola & Tocchini-Valenti 2001; Pietroni 2003; Comelli, Pietroni & Riotto 2003; Franca & Rosenfeld 2004; Zhang 2005; Guo et al. 2006; Li 2004; Wang, Gong & Abdalla 2006a; Wang, Lin & Abdalla 2006b;

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the Universe. However, different models of dark energy may lead to the same age of Universe at $z = 0$. To lift this degeneracy, we should examine the age of the Universe at different stages of its evolution and compare it with the estimated age of high-redshift objects. This procedure constrains the age at different stages, being a powerful tool to test the viability of different models (Friaca, Alcaniz & Lima 2005; Wang et al. 2006b).

This paper is organized as follows. In Section 2, we introduce a braneworld model with energy exchange between the brane and bulk, the cosmology of this model, its free parameters and background dynamics of the Universe governed by the effective Friedmann equation. We also show how this model can exhibit acceleration expansion of our Universe. Most limitations regarding this interaction in our model are introduced. We investigate the geometrical effects of underlying braneworld cosmology in Section 3. In Section 4, we test the viability of our model by putting some constraints on the parameters of the model. For this aim, we use the new Gold sample and Legacy Survey of SNIa data (Riess et al. 2004; Astier et al. 2006), its combination with the position of the observed acoustic angular scale on CMB and the baryonic oscillation length scale. In Section 5, we compare the age of the Universe in this model with the age of old cosmological objects. The last section is devoted to conclusions and discussions.

2 BRANEWORLD WITH BRANE–BULK ENERGY EXCHANGE

We start from the following action:

$$S = \frac{1}{2\kappa^2} \int d^5x \sqrt{-\tilde{g}} (R - 2\Lambda) + \int d^4x \sqrt{-g} L_{brane}^m + \int d^4x \sqrt{-\tilde{g}} (L_{brane}^m - \sigma).$$

(1)

where $R$ is the five-dimensional scalar curvature and $\Lambda < 0$ is the bulk cosmological constant. $g$ and $\tilde{g}$ are the bulk and the brane metrics, respectively. Throughout this paper, we choose the unit $\kappa^2 = 1$ as the gravitational constant in five dimension. We have also included arbitrary matter content both in the bulk and on the brane through $L_{brane}^m$ and $L_{brane}^m$, respectively. $\sigma$ is the positive brane tension. The field equations can be obtained by varying the action, equation (1), with respect to the bulk metric $g_{AB}$. The result is

$$G_{AB} + \Lambda g_{AB} = T_{AB}.$$

(2)

For convenience, we choose the extra-dimensional coordinate $y$ such that the brane is located at $y = 0$ and bulk has $Z_2$ symmetry. We are interested in the cosmological solution with a metric

$$ds^2 = -n^2(t, y) dt^2 + a^2(t, y) g_{ij} dx^i dx^j + b^2(t, y) dy^2,$$

(3)

where $g_{ij}$ is a maximally symmetric three-dimensional metric for the surface ($t = const.$ and $y = const.$), whose spatial curvature is parametrized by $K = -1, 0, 1$. The metric coefficients $n$ and $b$ are chosen as $n(t, 0) = 1$ and $b(t, 0) = 1$, where $t$ is cosmic time on the brane. The total energy-momentum tensor has bulk and brane components and can be written as

$$T_{AB} = T_{brane} |_{brane} + T_{brane} |_\sigma + T_{brane} |_{bulk}.$$

(4)

The first and the second terms are the contribution from the energy-momentum tensor of the matter field confined to the brane and the brane tension

$$T^A_{brane} |_{brane} = \text{diag}(-\rho, p, p, p, 0) \frac{\delta(y)}{b},$$

(5)

$$T^A_{brane} |_{\sigma} = \text{diag}(-\sigma, -\sigma, -\sigma, -\sigma, 0) \frac{\delta(y)}{b},$$

(6)

$$\sigma = \frac{1}{b}. $$

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where $\rho$ and $p$ are the energy density and pressure on the brane, respectively. In addition, we assume an energy-momentum tensor for the bulk content with the following form:

$$T^I_{\mu} |_{\text{bulk}} = \begin{pmatrix} T^0_0 & 0 & T^0_i \\ 0 & T^j_j & 0 \\ -\frac{\sigma}{6} T^2_2 & 0 & T^2_3 \end{pmatrix}. \tag{7}$$

The quantities which are of interest here are $T^0_0$ and $T^0_i$, as these two enter the cosmological equations of motion. In fact, $T^0_0$ is the term responsible for energy exchange between the brane and the bulk. Integrating the $(00)$ and the $(ij)$ components of the field equations (2) across the brane and imposing $Z_2$ symmetry, we have the jump across the brane

$$\frac{a'_i}{a_0} = -\frac{1}{6} (\rho + \sigma), \tag{8}$$

$$\frac{n'_i}{a_0} = \frac{1}{6} (2 \rho + 3 p - \sigma), \tag{9}$$

where $2a'_i$ and $2n'_i$ are the discontinuities of the first derivative and primes denote derivatives with respect to $y$. In addition, as usual, the subscript ‘0’ denotes that quantities are evaluated at $y = 0$.

Substituting the junction conditions, i.e. equations (8) and (9) into the $(55)$ and $(05)$ components of the field equation (2), we obtain the modified Friedmann equation and the semi-conservation law on the brane

$$2H^2 + \dot{H} + \frac{K}{a_0^2} = -\frac{1}{36} \left[ \sigma (3 p - \rho) + (\rho + 3 p) \right]$$

$$+ \frac{1}{3} \left( \Lambda + \frac{\sigma^2}{6} - T^2_3 \right), \tag{10}$$

$$\frac{\dot{\rho}}{\rho} + 3H(\rho + p) = -2T^0_0, \tag{11}$$

where $H = \dot{a}_0/a_0$ is the Hubble parameter on the brane and dots denote time derivative. We will assume an equation of state $p = w \rho$ which represents a relation between the energy density and pressure of the matter on the brane. The bulk matter contributes to the energy content of the brane through the bulk pressure terms $T^2_3$ and $T^2_2$. In order to derive a solution that is largely independent of the bulk dynamics, we should neglect $T^2_3$ term by assuming that the bulk matter relative to the bulk vacuum energy is much less than the ratio of the brane matter to the brane vacuum energy (Kiritsis et al. 2003). Considering this, we get

$$2H^2 + \dot{H} + \frac{K}{a_0^2} = \gamma \rho (1 - 3w) - \beta \rho^2 (1 + 3w) + \frac{\lambda}{3}, \tag{12}$$

$$\frac{\dot{\rho}}{\rho} + 3H(\rho + w) = -2T^0_0, \tag{13}$$

where we have used the usual definition $\beta \equiv 1/36$, $\gamma \equiv \beta \sigma$ and $\lambda \equiv (\Lambda + \sigma^2/6)$. Assuming the Randall–Sundrum fine-tuning $\lambda = \Lambda + \sigma^2/6 = 0$ holds on the brane, one can easily check that the Friedmann equation (12) is equivalent to the following equations:

$$H^2 + \frac{K}{a_0^2} = \beta \rho^2 + 2\gamma \rho + \chi, \tag{14}$$

$$\dot{\chi} + 4H \chi = 4T^2_3(\beta \rho + \gamma). \tag{15}$$

Equation (14) is the modified Friedmann equation describing cosmological evolution on the brane. The auxiliary field $\chi$ incorporates non-trivial contributions of dark energy which differ from the standard matter fields confined to the brane. It is worth noting that the flow of the mass-energy from the bulk on to the brane may resemble as the dark energy. Indeed, it can influence the background evolution of the Universe and lead to acceleration (see e.g. Kiritsis et al. 2003). One may argue that whether the energy exchange between the brane and bulk becomes dark matter or not? To answer this question, one should consider an interaction between dark matter and dark energy on the brane which is not yet clear. Besides, in order to have the equation of state in the bulk, a particular model of the bulk matter is required which is not clear yet, because we do not exactly know the bulk geometry (Bogdanos & Tamvakis 2007). So now in our coarse-grained model we ignored this effect.

We are also interested in the scenarios where the energy density of the brane is much lower than the brane tension, namely $\rho \ll \sigma$, therefore equations (14) and (15) can be simplified in the following form:

$$H^2 + \frac{K}{a_0^2} = 2\gamma \rho + \chi, \tag{16}$$

$$\dot{\chi} + 4H \chi = 4T^2_3. \tag{17}$$

Then, we take ansatz $T^0_0 = AH\rho^\mu$ for the brane–bulk energy exchange (Cai et al. 2006), where $A$ and $\mu$ are arbitrary constants and thereafter we have omitted the ‘0’ subscript from the scalefactor on the brane for simplicity. For this ansatz, one can easily check that equation (17) has the following solution:

$$\chi = \frac{C}{a^2} + \frac{4\gamma A}{\mu + 4} a^\mu, \tag{18}$$

where $C$ is an integration constant usually referred to the dark radiation term. In a similar way, inserting $T^0_3$ into equation (13), we get

$$\rho = \rho_0 - \frac{2A}{\mu + 3} a^\mu, \tag{19}$$

where $\rho_0$ is the present matter density of the Universe with equation of state $w = 0$. Finally, inserting $p$ and $\chi$ into equation (16), we obtain the modified Friedmann equation on the brane

$$H^2 = \frac{8\pi G_N}{3} \left[ \rho_m - \frac{2A}{(\mu + 3)(\mu + 4)} a^\mu \right] - \frac{K}{a^2}, \tag{20}$$

where $G_N = 3\gamma/4\pi$ is the four-dimensional Newtonian constant, $\rho_m = \rho_0 a^{-3}$ is matter energy density and we have neglected the dark radiation term $\sim a^{-4}$, namely $C = 0$, because we are more interested in the probe of late-time era. Using the value of present critical density,

$$\rho_c = \frac{3H_0^2}{8\pi G_N}, \tag{21}$$

the effective Friedmann equation in terms of dimensionless quantities and redshift parameter $1 + z = a^{-1}$ can be written as

$$H^2 = H_0^2 \left[ \Omega_m(1+z)^3 - \Omega_k(1+z)^{-2} - (\Omega_m \Omega_k - 1)(1+z)^2 \right], \tag{22}$$

where

$$\Omega_m = \frac{\rho_0}{\rho_c}, \quad \Omega_k = \frac{3K}{8\pi G_N \rho_c}, \quad \Omega_m = \frac{\rho_m}{\rho_c}, \quad \Omega_k = \Omega_m - \Omega_k = 1 + \Omega_K. \tag{23}$$

As one can see from equation (22), the free parameters of this model are very similar to those of $\Lambda$CDM models, but this is quite accidental and is due to our specific ansatz for the energy exchange term.
The cosmological observations are mainly affected by the background dynamics of the Universe. So, before starting some main observational tests to explore braneworld cosmology we investigate how the free parameters of this model alter the background dynamics by using the measurable quantities introduced in this section. We believe they give deep insight throughout this model. For this purpose, we study the effect of the braneworld model on the geometrical parameters of the Universe all together.

3 GEOMETRICAL EFFECTS OF BRANEWORLD MODEL

The cosmological observations are mainly affected by the background dynamics of the Universe. So, before starting some main observational tests to explore braneworld cosmology we investigate how the free parameters of this model alter the background dynamics by using the measurable quantities introduced in this section. We believe they give deep insight throughout this model. For this purpose, we study the effect of the braneworld model on the geometrical parameters of the Universe all together.

3.1 comoving distance

The radial comoving distance is one of the basic parameters of cosmology. For an object with the redshift of \( z \), using the null geodesics in the Friedmann–Robertson–Walker metric, the comoving distance is obtained as

\[
r(z; \Omega_m, \Omega_{\Lambda}, \mu) = \frac{1}{H_0 \sqrt{\Omega_K}} \mathcal{F} \left( \sqrt{\Omega_K} \int_0^z \frac{dz'}{H(z')/H_0} \right),
\]

where

\[
\mathcal{F}(x) \equiv (x, \sin x, \sinh x) \quad \text{for} \quad K = (0, 1, -1)
\]

and \( H(z; \Omega_m, \Omega_{\Lambda}, \mu) \) is given by equation (22).

By numerical integration of equation (27), the comoving distance in terms of redshift for different values of \( \mu \) is shown in Fig. 3. Increasing the \( \mu \) results in a longer comoving distance. According to this behaviour by fine-tuning the value of \( \mu \) in addition to \( \Omega_{\Lambda} \) and \( \Omega_m \), one can expect to explain the observational results given by supernova as a standard candle to measure distance in the observational cosmology.

Figure 1. Acceleration parameter \( q = \dot{a}/(aH_0^2) \) in the braneworld model as a function of redshift for various values of \( \mu \). Here, we chose \( \Omega_K = 0.0, \Omega_m = 0.30 \) and \( \Omega_{\Lambda} = -0.70 \).

Figure 2. Upper panel shows acceleration parameter \( q = \dot{a}/(aH_0^2) \) in the braneworld model as a function of scalefactor for various values of \( \Omega_{\Lambda} \) and \( \mu = -0.40 \). Lower panel corresponds to the same function for the flat \( \Lambda \)CDM. We chose the flat Universe.

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Observational constraints on the braneworld model

3.2 Angular size

The apparent angular size of an object located at the cosmological distance is another important parameter that can be affected by the cosmological model during the history of the Universe. An object with the physical size of $D$ is related to the apparent angular size of $\theta$ by

$$D = d_A \theta,$$  \hspace{1cm} (29)

where $d_A = r(z; \Omega_m, \Omega, \mu)/(1 + z)$ is the angular diameter distance. The main applications of equation (29) are on the measurement of the apparent angular size of acoustic peak on CMB and baryonic acoustic peak at the high and low redshifts, respectively. By measuring the angular size of an object in different redshifts (the so-called Alcock–Paczynski test), it is possible to probe the validity of braneworld model (Alcock & Paczynski 1979). The variation of apparent angular size $\Delta \theta$ in terms of $\Delta z$ is given by

$$\Delta \theta = H(z; \Omega_m, \Omega, \mu)r(z; \Omega_m, \Omega, \mu).$$  \hspace{1cm} (30)

Fig. 4 shows $\Delta \theta/\Delta z$ in terms of redshift, normalized to the case with $\Omega_m = 0.3, \Omega = -0.70$ and $\mu = 0.0$ (flat Universe, $\Omega_k = 0$). The advantage of Alcock–Paczynski test is that it is independent of standard candles and a standard ruler such as the size of baryonic acoustic peak can be used to constrain the braneworld model.

3.3 Comoving volume element

The comoving volume element is another geometrical parameter which is used in number-count tests such as lensed quasars, Galaxies or clusters of Galaxies. The comoving volume element in terms of comoving distance and Hubble parameter is given by

$$f(z; \Omega_m, \Omega, \mu) = \frac{dV}{d\Omega} = r(z; \Omega_m, \Omega, \mu)/H(z; \Omega_m, \Omega, \mu).$$  \hspace{1cm} (31)

According to Fig. 5, the comoving volume element becomes large for larger value of $\mu$ in the flat Universe.

4 OBSERVATIONAL CONSTRAINTS ON THE MODEL USING BACKGROUND EVOLUTION OF THE UNIVERSE

In this section, at the beginning, we examine braneworld model by SNIa Gold sample and Supernova Legacy Survey (SNLS) data. Then, to make the model parameter intervals more confined, we will combine observational results of SNIa distance modules with power spectrum of cosmic microwave background (CMB) radiation and baryon acoustic oscillation measured by Sloan Digital Sky survey (SDSS). Table 1 shows different priors of the model parameters used in the likelihood analysis.

### Table 1. Priors of the parameter space, used in the likelihood analysis

| Parameter | Prior |
|-----------|-------|
| $\Omega_{de}$ | Flat |
| $\Omega_m$ | $[0.00, 1.00]$ |
| $\Omega_b h^2$ | $0.020 \pm 0.005$ |
| $\Omega_\Lambda$ | $[-3.00, 1.00]$ |
| $h$ | Free |
| $\mu$ | Free |

We will use the above priors in the likelihood analysis.

4.1 Supernova Type Ia: Gold and SNLS samples

The SNIa experiments provided the main evidence of the existence of dark energy. Since 1995, two teams of the High-Z Supernova Search and the Supernova Cosmology Project have discovered several SNIa at high redshifts (Schmidt et al. 1998; Perlmutter et al. 1999a). Recently, Riess et al. (2004) have announced the discovery...
of 16 SNIa with the Hubble Space Telescope. They determined the luminosity distance of these supernovae and, with the previously reported algorithms, obtained a uniform 157 Gold sample of SNIa (Tonry et al. 2003; Barris et al. 2004; Riess et al. 2004). Recently, a new data set of Gold sample with smaller systematic error containing 156 supernova Ia has been released (The Gold Dataset 2006).

In this work, we use this data set as new Gold sample SNIa.

More recently, the SNLS collaboration released the first year data of its planned 5-year SNLS (Astier et al. 2006). An important aspect to be emphasized on the SNLS data is that they seem to be in better agreement with WMAP results than the Gold sample (Jassal, Bagla & Padmanabhan 2006). We compare the predictions of the braneworld model for apparent magnitude with new SNIa Gold sample and SNLS data set. The observations of supernova measure essentially the apparent magnitude m including reddening, K-correction, etc., which are related to the (dimensionless) luminosity distance, $D_L$, of an object at redshift $z$ through

$$m = M + 5 \log D_L(z; \Omega_m, \Omega_\Lambda, \mu),$$

where

$$D_L(z; \Omega_m, \Omega_\Lambda, \mu) = \left( \frac{1 + z}{\sqrt{\Omega_k}} \right) \frac{1}{H(z)} \int_0^z \frac{dz'}{H(z')},$$

Also,

$$M = m + 5 \log \left( \frac{c/H_0}{1 \text{ Mpc}} \right) + 25,$$

where $M$ is the absolute magnitude. The distance modulus, $\mathcal{R}$, is defined as

$$\mathcal{R} = m - M = 5 \log D_L(z; \Omega_m, \Omega_\Lambda, \mu) + 5 \log \left( \frac{c/H_0}{1 \text{ Mpc}} \right) + 25,$$

or

$$\mathcal{R} = 5 \log D_L(z; \Omega_m, \Omega_\Lambda, \mu) + \bar{M}.$$

In order to compare the theoretical results with the observational data, we must compute the distance modulus, as given by equation (35). For this purpose, the first step is to compute the quality of the fitting through the least-squared fitting quantity $\chi^2$ defined by

$$\chi^2(\bar{M}, \Omega_m, \Omega_\Lambda, \mu) = \sum_i \frac{[\theta_{\text{obs}}(z_i) - \theta_{\text{th}}(z_i; \Omega_m, \Omega_\Lambda, \mu, \bar{M})]^2}{\sigma_i^2},$$

where $\sigma_i$ is the observational uncertainty in the distance modulus. To constrain the parameters of model, we use the likelihood statistical analysis:

$$\mathcal{L}(\bar{M}, \Omega_m, \Omega_\Lambda, \mu) = N e^{-\chi^2(\bar{M}, \Omega_m, \Omega_\Lambda, \mu)/2},$$

where $N$ is a normalization factor. The parameter $\bar{M}$ is a nuisance parameter and should be marginalized (integrated out) leading to a new $\tilde{\chi}^2$ defined as

$$\tilde{\chi}^2 = -2 \ln \int_{\bar{M}}^{\infty} \mathcal{L}(\bar{M}, \Omega_m, \Omega_\Lambda, \mu) d\bar{M}.$$

Using equations (37) and (39), we find

$$\tilde{\chi}^2(\Omega_m, \Omega_\Lambda, \mu) = \chi^2(\bar{M} = 0, \Omega_m, \Omega_\Lambda, \mu) - \frac{B(\Omega_m, \Omega_\Lambda, \mu)^2}{C} + \ln(C/2\pi),$$

where

$$B(\Omega_m, \Omega_\Lambda, \mu) = \sum_i \frac{[\theta_{\text{obs}}(z_i) - \theta_{\text{th}}(z_i; \Omega_m, \Omega_\Lambda, \mu, \bar{M} = 0)]}{\sigma_i^2},$$

and

$$C = \sum_i \frac{1}{\sigma_i^2}.$$

Equivalent to marginalization is the minimization with respect to $\bar{M}$. One can show that $\chi^2$ can be expanded in $\bar{M}$ as (Nesseris & Perivolaropoulos 2004)

$$\chi^2_{\text{SNLS}}(\Omega_m, \Omega_\Lambda, \mu) = \chi^2(\bar{M} = 0, \Omega_m, \Omega_\Lambda, \mu) - 2\bar{M}B + \bar{M}^2C,$$

which has a minimum for $\bar{M} = B/C$.

$$\chi^2_{\text{SNLS}}(\Omega_m, \Omega_\Lambda, \mu) = \chi^2(\bar{M} = 0, \Omega_m, \Omega_\Lambda, \mu) - \frac{B(\Omega_m, \Omega_\Lambda, \mu)^2}{C}.$$

Using equation (44), we can find the best-fitting values of model parameters as the values that minimize $\chi^2_{\text{SNLS}}(\Omega_m, \Omega_\Lambda, \mu)$. The best-fitting values for the parameters of model by using supernova data are $\Omega_m = 0.51_{-0.30}^{+0.10}$, $\Omega_\Lambda = -0.75_{-0.12}^{+0.10}$ and $\mu = 0.76_{-0.05}^{+0.14}$ with $\chi^2_{\text{min}}/N_{\text{dof}} = 0.92$ at 1σ level of confidence. These values imply that $\Omega_k = -0.26_{-0.14}^{+0.33}$. The best-fitting values for the parameters of model by using SNLS supernova data are $\Omega_m = 0.06_{-0.06}^{+0.04}$, $\Omega_\Lambda = -1.84_{-0.99}^{+1.58}$ and $\mu = -1.34_{-1.10}^{+0.10}$ with $\chi^2_{\text{min}}/N_{\text{dof}} = 0.87$ at 1σ level of confidence. The corresponding value of $\Omega_k$ at 1σ confidence level is $\Omega_k = -0.90_{-0.56}^{+0.95}$. Figs 6 and 7 show the comparison of the theoretical prediction of distance modulus by using the best-fitting values of model parameters and observational values from new Gold sample and SNLS supernova, respectively. Figs 8 and 9 show relative likelihood for free parameters of brane model.

### 4.2 Combined analysis: SNIa+CMB+SDSS

To obtain more confined acceptable intervals of model free parameters, now we combine SNIa data (from SNIa new Gold sample and SNLS) with CMB data from the WMAP and recently observed baryonic peak from the SDSS. We also examine the peak positions of power spectrum in addition to the common shift parameter.
Before last scattering, the photons and baryons are tightly coupled by Compton scattering and behave as a fluid. The oscillations of this fluid, occurring as a result of the balance between the gravitational interactions and the photon pressure, lead to the familiar spectrum of peaks and troughs in the averaged temperature anisotropy spectrum which we measure today. The odd and even peaks correspond to maximum compression of the fluid and to rarefaction, respectively (Hu, Sugiyama & Silk 1997). In an idealized model of the fluid, there is an analytic relation for the location of the $m$th peak: $l_m \approx m \lambda_A$ (Hu & Sugiyama 1995; Hu et al. 2001) where $l_m$ is the acoustic scale which may be calculated analytically and depends on both pre- and post-recombination physics as well as the geometry of the Universe. The acoustic scale corresponds to the Jeans length of photon–baryon structures at the last scattering surface some $\sim 379$ kyr after the big bang (Spergel et al. 2003). The apparent angular size of acoustic peak can be obtained by dividing the comoving size of sound horizon at the decoupling epoch $r_s(z_{\text{dec}})$ by the comoving distance of observer to the last scattering surface $r(z_{\text{dec}})$.

$$\theta_A = \frac{\pi}{\lambda_A} = \frac{r_s(z_{\text{dec}})}{r(z_{\text{dec}})}.$$  

The size of sound horizon at the numerator of equation (45) corresponds to the distance that a perturbation of pressure can travel from the beginning of the Universe up to the last scattering surface and is given by

$$r_s(z_{\text{dec}}; \Omega_m, \Omega_b, \mu) = \frac{1}{H_0 \sqrt{2g_1}} \times \mathcal{F} \left( \frac{v_s(z)}{H_0} \right) \int_{z_{\text{dec}}}^{\infty} \frac{v_s(z')dz'}{H(z')/H_0},$$

where $v_s(z) = 3 + 9/4 \times \rho_b(z)/\rho_\text{rad}(z)$ is the sound velocity in the unit of speed of light from the big bang up to the last scattering surface (Hu & Sugiyama 1995; Doran et al. 2001) and the redshift of the last scattering surface, $z_{\text{dec}}$, is given by (Hu & Sugiyama 1995)

$$z_{\text{dec}} = 1048 \left[ 1 + 0.00124(\omega_b)^{-0.738} \right] \left[ 1 + g_1(\omega_m)^{0.5} \right],$$

$$g_1 = 0.0783(\omega_b)^{-0.328} \left[ 1 + 39.5(\omega_m)^{0.763} \right]^{-1},$$

$$g_2 = 0.560 \left[ 1 + 21.1(\omega_b)^{0.81} \right]^{-1},$$

where $\omega_m \equiv \Omega_m h^2$, $\omega_b \equiv \Omega_b h^2$ and $\rho_\text{rad}$ is the radiation density, $\Omega_b$ is relative baryonic density to the critical density at the present time. Changing the parameters of the model can change the size of apparent acoustic peak and subsequently the position of $l_A = \pi/\theta_A$ in the power spectrum of temperature fluctuations at the last scattering surface. The simple relation $l_m \approx m \lambda_A$, however, does not hold very well for the peaks although it is better for higher peaks (Hu et al. 2001; Doran & Lilley 2002). Driving effects from the decay of the gravitational potential as well as contributions from the Doppler shift of the oscillating fluid introduce a shift in the spectrum. A good parametrization for the location of the peaks and troughs is given by (Hu et al. 2001; Doran & Lilley 2002)

$$l_m = l_A(m - \phi_m),$$

where $\phi_m$ is phase shift determined predominantly by recombination physics, and are independent of the geometry of the Universe. The location of acoustic peaks can be determined in model by equation (48) with $\phi_m(\omega_m, \omega_b)$. Doran & Lilley (2002) have recently shown that the first and third phase shifts are approximately model independent. The values of these shift parameters have been reported as: $\phi_1(\omega_m, \omega_b) \approx 0.27$ and $\phi_3(\omega_m, \omega_b) \approx 0.341$ (Hu et al. 2001;}
Because of weak dependency of phase shift to the cosmological model usually another model independent parameter which is so-called shift parameter $R$ from CMB observation as

$$R \propto \frac{I_1}{I_1}$$

are used as another observational test, where $I_1$ corresponds to the flat pure-CDM model with $\Omega_m = 1.0$ and the same $\omega_b$ and $\omega_c$ as the original model. It is easily shown that shift parameter is as follows (Bond, Efstathiou & Tegmark 1997):

$$R = \sqrt{\Omega_m D_A(z_{dec}, \Omega_m, \Omega_\Lambda, \mu)}.$$  \hfill (54)

The observational results of CMB experiments correspond to a shift parameter of $R = 1.716 \pm 0.062$ [given by WMAP, Cosmic Background Imager (CBI) and Arcminute Cosmology Bolometer Array Receiver (ACBAR)] (Pearson et al. 2003; Spergel et al. 2003; Kuo et al. 2004). One of the advantages of using the parameter $R$ is its independency of Hubble constant. In order to put constraint on the model from CMB, we compare the observed shift parameter with that of model using likelihood statistic as (Bond et al. 1997; Melchiorri et al. 2003; Odman et al. 2003)

$$\mathcal{L} \sim e^{-\chi^2_{\text{CMB}}/2},$$

where

$$\chi^2_{\text{CMB}} = \frac{(R_{\text{obs}} - R_{\text{th}})^2}{\sigma_{\text{CMB}}}.$$  \hfill (56)

where $R_{\text{th}}$ and $R_{\text{obs}}$ are determined using equation (54) and given by observation, respectively. Fig. 10 shows constant value of $\lambda_i$ in the joint space parameters ($\Omega_m$, $\Omega_\Lambda$) and ($\Omega_m$, $\omega_b$) for the braneworld

2001; Doran & Lilley 2002; Percival et al. 2002). According to the WMAP observations: $I_1 = 220.1 \pm 0.8$ and $I_1 = 809 \pm 7$, so the corresponding observational values of $I_1$ read as

$$I_1^{\text{obs}} | I_1 = \frac{I_1}{1 - \phi_1} = 299.45 \pm 2.67.$$

$$I_1^{\text{obs}} | I_3 = \frac{I_3}{3 - \phi_3} = 304.24 \pm 2.63$$  \hfill (50)

their likelihood statistics are as follows:

$$\chi^2_1 = \frac{[p_{\text{obs}} - p_{\text{th}}]^2}{\sigma^2_{\text{th}}},$$

and

$$\chi^2_3 = \frac{[p_{\text{obs}} - p_{\text{th}}]^2}{\sigma^2_{\text{th}}}. $$

\hfill (52)

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure9.png}
\caption{Marginalized likelihood functions of three parameters of a braneworld model ($\Omega_m$, $\Omega_\Lambda$, and $\mu$). The solid line corresponds to the likelihood function of fitting the model with SNII data (SNLS), the dash-dotted line with the joint SNII+SDSS data and dashed line corresponds to SNII+CMB+5SDSS. The intersections of the curves with the horizontal solid and dashed lines give the bounds with 1$\sigma$ and 2$\sigma$ level of confidence, respectively.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure10.png}
\caption{Constant acoustic angular scale in the joint space of $\Omega_m$ and $\Omega_\Lambda$ (upper panel). Lower panel shows dependence of acoustic angular scale on $\Omega_m$ and cosmological constant.}
\end{figure}
and the $\Lambda$CDM model, respectively. Increasing (decreasing) $\Omega_\Lambda$ ($\Omega_m$) leads to an increase in the value of present matter density to make constant value for $l_0$. What we found is in agreement with Fig. 2.

Another robust observational approach to investigate cosmological models is inferring the behaviour of the matter power spectrum and time evolution of gravitational clustering in both linear and non-linear regimes. The simplest things to do are solving the relevant Boltzmann and Einsteinian equations for various matter contents in the Universe (Dodelson 2003). Matter power spectrum and other non-linear effects can be a special tool to discriminate various models as well as to make more confined acceptable range for their free parameters (see Seljak & Zaldarriaga 1999; Ma 2007; Amendola 2000, 2001, 2002, 2003; Eke, Navarro & Steinmetz 2001; Peebles & Ratra 2003; Loeb & Waga 2005; Olivares, Atrio-Barandela & Pavon 2005, 2006; Lee, Liu & Ng 2006; Jeong & Komatsu 2006; Chimento & Pavon 2006; Koivisto 2006; Lee, Ratra 2003; Loeb & Zaldarriaga 2005; Reis, Makler & Waga 2005; Eke, Navarro & Steinmetz 2001; Peebles & Ratra 2000, 2001, 2002, 2003; Eisenstein et al. 2005; Hui & Sugiyama 1996; Eisenstein & Hu 1998; Eisenstein & White 2004; Amarzguioui et al. 2006).

A dimensionless and independent of $H_0$ version of SDSS observational parameter is

$$A = D_V(z_{SDSS}) \sqrt{\Omega_m H_0^2 / z_{SDSS}}$$

$$= \sqrt{\Omega_m} \left[ H_0 D_V(z_{SDSS}; \Omega_m, \Omega_\Lambda, \mu) / H(z_{SDSS}; \Omega_m, \Omega_\Lambda, \mu) \right]^{1/3} \xi_{SDSS}(1 + z_{SDSS}^2)^{1/2}, \quad (58)$$

due to the fact that even though baryon acoustic oscillation is mostly contributed by linear scale, the influence of non-linear collapsing has quite broad kernel. In other words, one might say that baryon acoustic oscillation are 90–99 per cent linear in comparison to the CMB which is 99.99 per cent linear, so this difference may affect various models in different ways. Careful works to constrain the free parameters of the underlying model need to be carried out to determine the effect of non-linear coupling resulting from constraint by SDSS observation. Nevertheless, roughly speaking, the acceptance intervals for free parameter cover the real intervals determined by assuming non-linearity mode for SDSS observation (Hu & Sugiyama 1996; Eisenstein & Hu 1998; Eisenstein & White 2004; Amarzguioui et al. 2006).

This is the third observational constraint for our analysis. In the rest of this section, we perform a combined analysis of SNIa, CMB and SDSS to constrain the parameters of the braneworld model by minimizing the combined $\chi^2 = \chi^2_{\text{SNIa}} + \chi^2_{\text{CMB}} + \chi^2_{\text{SDSS}}$. The best values of the model parameters from the fitting with the corresponding error bars from the likelihood function marginalizing over the Hubble parameter in the multidimensional parameter space are: $\Omega_m = 0.284^{+0.03}_{-0.02}, \Omega_\Lambda = -0.71^{+0.03}_{-0.04}, \mu = -0.40^{+0.28}_{-0.26}$ at 1σ confidence level with $\chi^2_{\min} / N_{d.o.f} = 0.93$ demonstrated $\Omega_m = 0.00^{+0.04}_{-0.04}$. The Hubble parameter corresponding to the minimum value of $\chi^2$ is $H_0 = 62.72$. Here, we obtain an age of $14.82^{+0.45}_{-0.44}$ Gyr for the Universe (see Section 5 for more details). Using the SNLS data, the best-fitting values of model parameters are: $\Omega_m = 0.27^{+0.02}_{-0.02}, \Omega_\Lambda = -0.74^{+0.04}_{-0.02}, \mu = 0.00^{+0.04}_{-0.03}$ at 1σ confidence level with $\chi^2_{\min} / N_{d.o.f} = 0.86$, states $\Omega_k = -0.01^{+0.04}_{-0.03}$. The age of Universe calculated with the best-fitting parameters is 14.05^{+0.45}_{-0.45} Gyr (see the next section).

Table 2 and 3 give the best-fitting values for the free parameters and age of Universe computing with these values. Joint confidence intervals in free parameter spaces are shown in Figs 11–16.

5 AGE OF UNIVERSE

The age of Universe integrated from the big bang up to now in terms of free parameters of the braneworld model is given by

$$t_0(\Omega_m, \Omega_\Lambda, \mu) = \int_0^\infty dt$$

$$= 1 / H_0 \sqrt{|H_k|} \mathcal{F} \left[ \sqrt{|H_k|} \int_0^\infty \frac{dz}{(1 + z)H(z)} \right]. \quad (60)$$
The best-fitting values for the parameters of the model using SNIa from new Gold sample and SNLS data, SNIa+CMB and SNIa+CMB+SDSS experiments at 1σ and 2σ confidence level.

| Observation               | \(\Omega_m\)  | \(\Omega_A\)  | \(\mu\)    |
|---------------------------|----------------|----------------|------------|
| SNIa(new Gold)            | 0.51^{+0.10}_{-0.30} | -0.75^{+0.32}_{-1.41} | 0.76^{+0.24}_{-1.95} |
| SNIa(new Gold)+CMB        | 0.51^{+0.14}_{-0.54} | -0.75^{+0.45}_{-1.55} | 0.76^{+0.24}_{-2.27} |
| SNIa(new Gold)+CMB+SDSS   | 0.49^{+0.07}_{-0.08} | -0.59^{+0.05}_{-0.06} | -1.76^{+0.12}_{-1.31} |
| SNIa (SNLS)               | 0.29^{+0.05}_{-0.04} | -0.71^{+0.06}_{-0.06} | -0.40^{+0.08}_{-0.06} |
| SNIa(SNLS)+CMB            | 0.06^{+0.44}_{-0.06} | -1.84^{+1.58}_{-0.59} | -1.34^{+7.34}_{-0.10} |
| SNIa(SNLS)+CMB+SDSS       | 0.23^{+0.20}_{-0.23} | -0.76^{+0.11}_{-0.16} | -0.26^{+0.72}_{-1.00} |
| SNIa(SNLS)+CMB+SDSS       | 0.27^{+0.02}_{-0.02} | -0.74^{+0.04}_{-0.02} | 0.00^{+0.30}_{-0.30} |

Table 3. The best values for the curvature of the brane model with the corresponding age for the Universe from fitting with SNIa from new Gold sample and SNLS data, SNIa+CMB and SNIa++CMB+SDSS experiments at 1σ and 2σ confidence level.

| Observation               | \(\Omega_k\)  | Age (Gyr)    |
|---------------------------|----------------|--------------|
| SNIa(new Gold)            | -0.26^{+0.33}_{-1.44} | 13.44^{+2.10}_{-7.13} |
| SNIa(new Gold)+CMB        | +0.01^{+0.09}_{-0.10} | 13.53^{+0.85}_{-1.18} |
| SNIa(new Gold)+CMB+SDSS   | +0.00^{+0.04}_{-0.04} | 14.82^{+0.55}_{-0.44} |
| SNIa (SNLS)               | -0.90^{+1.64}_{-0.59} | 14.38^{+2.00}_{-1.81} |
| SNIa(SNLS)+CMB            | -0.01^{+0.23}_{-0.28} | 14.38^{+3.03}_{-1.38} |
| SNIa(SNLS)+CMB+SDSS       | -0.01^{+0.04}_{-0.03} | 14.05^{+0.43}_{-0.45} |

Fig. 11. Joint confidence intervals of \(\Omega_m\) and \(\Omega_A\), fitted with SNIa new Gold sample+CMB+SDSS. Solid line, dashed line and long dashed line correspond to 3σ, 2σ and 1σ level of confidence, respectively.

Fig. 12. Joint confidence intervals of \(\mu\) and \(\Omega_A\), fitted with SNIa new Gold sample+CMB+SDSS. Solid line, dashed line and long dashed line correspond to 3σ, 2σ and 1σ level of confidence, respectively.

Fig. 13. Joint confidence intervals of \(\mu\) and \(\Omega_m\), fitted with SNIa SNLS+CMB+SDSS. Solid line, dashed line and long dashed line correspond to 3σ, 2σ and 1σ level of confidence, respectively.

Fig. 14. Joint confidence intervals of \(\Omega_m\) and \(\Omega_A\), fitted with SNIa SNLS+CMB+SDSS. Solid line, dashed line and long dashed line correspond to 3σ, 2σ and 1σ level of confidence, respectively.

Fig. 17 shows the dependency of \(H_0\) (Hubble parameter times the age of Universe) on \(\Omega_A\) and \(\mu\) for a flat Universe. Obviously increasing \(\Omega_A\) and \(\mu\) results in a shorter and longer age for the Universe, respectively. As a matter of fact, according to equation (22), \(\Omega_A\) has the inverse role of dark energy in the \(\Lambda\)CDM scenario and \(\mu\) has the inverse role of \(w\) in the \(\Lambda\)CDM (see Figs 17 and 18).

The ‘age crisis’ is one the main reasons of the acceleration phase of the Universe. The problem is that the universe’s age in the cold dark matter (CDM) Universe is less than the age of old stars in it. Studies on the old stars (Carretta et al. 2000) suggest an age of...
13.4 Gyr for the Universe. Richer et al. (2002) and Hansen et al. (2002) also proposed an age of 12.7 ± 0.7 Gyr, using the white dwarf cooling sequence method (for full review of the cosmic age see Spergel et al. 2003). Table 3 shows that the age of the Universe from the combined analysis of SNIa+CMB+SDSS is 14.82^{+0.55}_{-0.44} and 14.05^{+0.41}_{-0.45} Gyr for new Gold sample and SNLS data, respectively, while ΛCDM implies 13.7 ± 0.2 Gyr (Spergel et al. 2003). These values are in agreement with the age of old stars (Carretta et al. 2000; Krauss & Chaboyer 2001; Chaboyer & Krauss 2002).

To do another consistency test, we compare the age of Universe derived from this model with the age of old stars and Old High Redshift Galaxies (OHRG) in various redshifts. Here, we consider three OHRG for comparison with the braneworld model, namely the LBDS 53W091, a 3.5-Gyr old radio Galaxy at z = 1.55 (Dunlop et al. 1996; Spinrad 1997), the LBDS 53W069, a 4.0-Gyr old radio Galaxy at z = 1.43 (Dunlop 1999) and a quasar, APM 08279 + 5255 at z = 3.91 with an age of τ = 2.1^{+0.9}_{-0.3} Gyr (Hasinger, Schartel & Komossa 2002; Komossa & Hasinger 2002). The latter has once again led to the ‘age crisis’. An interesting point about this quasar is that it cannot be accommodated in the ΛCDM model (Jain & Dev 2006). Moreover, modifications of the gravity Lagrangian have also been advocated. Although deeply different in their underlying physics, these scenarios share the common feature of well reproducing the available astrophysical data. On the other hand, alternative cosmology from the braneworld models provides a possible mechanism for the present acceleration of the Universe congruously suggested by various cosmological observations.

6 CONCLUSIONS AND DISCUSSIONS

The impressive data indicating a spatially flat Universe in accelerated expansion have posed the problem of dark energy and stimulated the search for cosmological models which are able to explain such unexpected behaviour. Many rival theories have been proposed to solve the puzzle of the nature of dark energy ranging from a rolling scalar field to a unified picture where a single exotic fluid accounts for the whole dark sector (dark matter and dark energy). Moreover, modifications of the gravity Lagrangian have also been addressed. Although deeply different in their underlying physics, all these scenarios share the common feature of well reproducing the available astrophysical data. On the other hand, alternative cosmology from the braneworld models provides a possible mechanism for the present acceleration of the Universe congruously suggested by various cosmological observations.
on the RS II braneworld model with energy exchange between the brane and bulk. We got the modified Friedmann equation (22) on the brane which can explain the cosmological behaviour and describe the physical origin for the dark energy which is in good agreement with observations. We explored the consistency of this scenario with the implication of up-to-date luminosity of SNIa observed by two independent groups, new Gold sample and SNLS data set, acoustic peak in the CMB anisotropy power spectrum and baryon acoustic oscillation measured by SDSS. The effect of model free parameters on the matter power spectrum and the exploration of matter and dark energy interaction will be investigated in our forthcoming paper.

The best parameters obtained from the fitting with the new Gold sample data combined with CMB and SDSS observations are: $\Omega_m = 0.29^{+0.03}_{-0.02}, \Omega_L = -0.71^{+0.03}_{-0.03}$ and $\mu = -0.40^{+0.28}_{-0.26}$ at 1σ confidence level with $\chi^2_{\text{min}}/N_{\text{d.o.f}} = 0.93$ expressing spatially flat Universe with $\Omega_L = +0.00^{+0.04}_{-0.04}$. SNLS SNIa+CMB+SDSS give: $\Omega_m = 0.27^{+0.02}_{-0.02}, \Omega_L = -0.74^{+0.02}_{-0.02}$ and $\mu = 0.00^{+0.30}_{-0.30}$ at 1σ confidence level with $\chi^2_{\text{min}}/N_{\text{d.o.f}} = 0.86$, asserting $\Omega_L = -0.01^{+0.04}_{-0.03}$. The well-known $\Lambda$CDM model implying $-0.06 < \Omega_L < +0.02$ (Spergel et al. 2003) and some other interesting models such as Dvali–Gabadadze–Porrati (DGP) model indicate $\Omega_L = 0.01^{+0.09}_{-0.09}$ and $\Omega_L = 0.01^{+0.04}_{-0.04}$ using Gold sample and SNLS data, respectively (Guo et al. 2006; Movahed & Gassemi 2007; Movahed, Farhang & Rahvar 2007b).

We also performed the age test, comparing the age of old stars and OHRG with the age derived from this model. From the best-fitting parameters of the model using new Gold sample and SNLS SNIa, we obtained an age of Universe of $14.82^{+0.44}_{-0.44}$ and $14.05^{+0.43}_{-0.45}$ Gyr for the Universe, respectively. These results are in agreement with the age of the old stars. The age of Universe in this model is larger than that given in the other models (Miranda et al. 2001; Spergel et al. 2003; Movahed et al. 2007b; Rahvar & Movahed 2007).

To check the age crisis in this model, we chose two high-redshift radio galaxies at $z = 1.55$ and 1.43 with a quasar at $z = 3.91$. Two first objects were consistent with the age of Universe, i.e. they were younger than the Universe while the third one was not, but our model gave the better result than $\Lambda$CDM and a class of Quintessence model (Miranda et al. 2001; Rahvar & Movahed 2007).

Finally, we must point out that the energy exchange term $\Omega_L$ plays a crucial role in our work. In other words, in the RS II model without energy exchange where we have $\Omega_L = 0$, we cannot get late time acceleration expansion profile for our Universe! So, we conclude that the usual RS II model should be ruled out from present observational data.

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