Interaction between dark energy and dark matter: observational constraints from $H(z)$, BAO, CMB and SNe Ia

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ABSTRACT

In order to test if there is energy transfer between dark energy and dark matter, we investigate cosmological constraints on two forms of nontrivial interaction between the dark matter sector and the sector responsible for the acceleration of the universe, in light of the newly revised $H(z)$ data, the baryonic acoustic oscillation (BAO) peak detected by large-scale correlation function of luminous red galaxies from Sloan Digital Sky Survey (SDSS), the cosmic microwave background (CMB) observations and the most recent 557 Union2 SNe Ia data. For the $\gamma_m$IDE model in which the interaction term expresses as $Q = 3\gamma_m H\rho_m$ with the corresponding constant $\gamma_m$ quantifying the extent of interaction, we obtain $\gamma_m = -0.013^{+0.013}_{-0.011}$, $\gamma_m = -0.009^{+0.013}_{-0.012}$ and $\gamma_m = -0.011^{+0.012}_{-0.011}$ with $H(z)$+BAO+CMB, SNe Ia+BAO+CMB and $H(z)$+SNe Ia+BAO+CMB, respectively. For the $\gamma_d$IDE model in which the interaction term takes the form $Q = 3\gamma_d H\rho_X$ with the corresponding constant $\gamma_d$ quantifying the extent of interaction, the best-fit values are $\gamma_d = -0.040^{+0.042}_{-0.042}$, $\gamma_d = -0.023^{+0.039}_{-0.040}$ and $\gamma_d = -0.030^{+0.037}_{-0.037}$. These results indicate that, on the one hand, the concordance LCDM model without any interaction remains a good fit to the recent observational data; on the other hand, the interaction that the energy transferring from dark matter to dark energy is slightly favoured over the interaction delivering energy from dark energy to dark matter, which is in agreement with the results by using other observational data such as the 182 Gold SNe Ia and 397 Constitution SNe Ia samples in the previous works.

Subject headings: cosmological parameters - (Cosmology:) dark energy

1. Introduction

Many astrophysical and cosmological observations, such as Type Ia Supernovae (SNe Ia) (Riess et al. 1998; Perlmutter et al. 1999; Riess et al. 2004; Knop et al. 2007), cosmic microwave background (CMB) from Wilkinson Microwave Anisotropy Probe (WMAP) (Spergel et al.
2003, 2007; Komatsu et al. 2009, 2010) and the large scale structure from Sloan Digital Sky Survey (SDSS) (Tegmark et al. 2004; Eisenstein et al. 2005) have indicated that the universe is undergoing an accelerating expansion, which consequently leads to the assumption of the existence of dark energy, an exotic energy with negative pressure and causes an accelerating expansion of our universe at late times. The most simple candidate for these uniformly distributed dark energy is considered to be in the form of a cosmological constant ($\Lambda$) with a equation of state $w = \rho_\Lambda / p_\Lambda \equiv -1$. However, the corresponding $\Lambda$CDM model is always entangled with the coincidence problem: The matter density $\rho_m$ decreases with the expansion of our universe with $a^{-3}$ and the density of cosmological constant $\rho_\Lambda$ does not change with the expansion of the universe, whereas the dark energy density is comparable with the dark matter density today, why? Although many alternative models include the scalar field models with dynamical EoS (e.g., the quintessence (Wetterich 1988; Ratra & Peebles 1988; Caldwell et al. 1998), phantom (Caldwell et al. 2002, 2003), k-essence (Armendariz-Picon et al. 2001; Chiba et al. 2002), as well as quintom model (Feng et al. 2005, 2006; Guo et al. 2005a)), have been proposed to alleviate the coincidence problem, the nature of dark energy is still unknown.

It is natural to consider the possibility of exchanging energy between dark energy and dust matter through interaction term. The interacting dark energy model was first introduced to test the coincidence problem, in which $\rho_m$ could decrease with the expansion of our universe slower than $a^{-3}$. Amendola (2000) investigated a coupled quintessence (CQ) model by assuming an exponential potential and a linear coupling, besides many other background and perturbation constraints carried out by Bean et al. (2008); La Vacca, et al. (2009); De Bernardis et al. (2011). On the other hand, it is always assumed that dark energy and dust matter exchange energy through an interaction term $Q$

$$
\dot{\rho}_X + 3H (\rho_X + p_X) = -Q, \\
\dot{\rho}_m + 3H \rho_m = Q,
$$

(1)

which preserves the total energy conservation equation $\dot{\rho}_{tot} + 3H (\rho_{tot} + p_{tot}) = 0$. The interaction term $Q$ is extensively considered in the literature (Copeland et al. 1998; Dalal et al. 2001; Chimento et al. 2003; Setare 2004; Cai & Wang 2005; Guo et al. 2005b; Nojiri & Odintsov 2005; Wei et al. 2005; Wei & Cai 2006; Szydlowski 2006; Bertolami et al. 2007; Guo et al. 2007; Chen et al. 2009, 2010). If $Q$ is a non-zero function of the scale factor, the interaction makes $\rho_m$ and $\rho_d$ to deviate from the standard scaling. The simplest assumption is

$$
Q = 3\gamma H \rho,
$$

(2)

where $\rho$ is the density of dust matter $\rho_m$ (Wei & Zhang 2007a,b; Zhang & Li 2010) or the density of dark energy $\rho_X$ (Zhang & Li 2010) with the corresponding constant $\gamma_m$ or $\gamma_d$. 

quantifying the extent of interaction between dust matter and dark energy. We assume that the EoS of dark energy $w_X \equiv p_X/\rho_X$ is a constant in spatially flat FRW metric. When working out the value of $\gamma$, we can see the extent of interaction and transfer direction between dark energy and dark matter. The $\Lambda$CDM model without interaction between dark energy and dark matter ($Q = 0$) is characterized by $\gamma = 0$, while $\gamma \neq 0$ and denote non-standard cosmology. For $\gamma < 0$, the energy is transferred from dark matter to dark energy; while for $\gamma > 0$, the energy is transferred from dark energy to dark matter, and the coincidence problem can be alleviated.

For the observational data, the observational Hubble parameter data $H(z)$ have become an effective probe both in cosmology and astrophysics compared with the SNe Ia data, the CMB data and the baryonic acoustic oscillation (BAO) data and it is more rewarding to investigate the observational $H(z)$ data directly. The reason is quite simple, it is obvious that these probes all use the distance scale (e.g., the luminosity distance $d_L$, the shift parameter $R$, or the distance parameter $A$) measurement to determine cosmological parameters, which needs the integrate of the Hubble parameter and therefore lose the fine structure and some more important information of $H(z)$ \cite{Lin_2009}. The Hubble parameter depends on the differential age as a function of redshift $z$ in the form

$$H(z) = -\frac{1}{1 + z} \frac{dz}{dt}. \quad (3)$$

which provides a direct measurement for $H(z)$ through a determination of $dz/dt$. Jimenez et al. \cite{Jimenez_2003} demonstrated the feasibility of the method by applying it to a $z \sim 0$ sample. By using the differential ages of passively evolving galaxies determined from the Gemini Deep Deep Survey (GDDS) \cite{Abraham_2004} and archival data \cite{Treu_2001, Nolan_2003a, Nolan_2003b, Simon_2005} determined 9 $H(z)$ data in the range $0 \leq z \leq 1.8$. These observational $H(z)$ data were also used to constrain the parameters of cosmological models \cite{Samushia_2006, Yi_2007} and some other relevant works include Wei & Zhang \cite{Wei_2007a, Wei_2007b}, Wu & Yu \cite{Wu_2007a, Wu_2007b}, Lazkoz & Majerotto \cite{Lazkoz_2007}, Kurek & Szydlowski \cite{Kurek_2008}, Sen & Scherrer \cite{Sen_2008}, Xu et al. \cite{Xu_2008}, Zhang & Zhu \cite{Zhang_2008} for examples. Recently, Stern et al. \cite{Stern_2010} obtained the $H(z)$ data at 11 different redshifts obtained from the differential ages of red-envelope galaxies; and other two Hubble parameter data at $z = 0.24$ and $z = 0.43$ were determined by Gaztañaga et al. \cite{Gaztanaga_2009} from observations of BAO peaks. Some recent works using these newly $H(z)$ data for cosmological constraint can be found in Gong et al. \cite{Gong_2010}, Liang, Wu & Zhang \cite{Liang_2010}, Cao, Zhu & Liang \cite{Cao_2011}, Ma & Zhang \cite{Ma_2011}, Xu & Wang \cite{Xu_2010}, Zhai et al. \cite{Zhai_2010}, Zhang, Ma & Lan \cite{Zhang_2010}.

In the previous works, Wei & Zhang \cite{Wei_2007a} compared the 9 observational $H(z)$ data with some cosmological models with/without interaction between dark energy and dust matter and found that the $H(z)$ data points with fairly large errors cannot severely constrain
model parameters alone. In this paper, we focus on the newly $H(z)$ data to study the interaction between the dust matter and dark energy and test the cosmic coincidence problem. In order to break the degeneracy of model parameters, we also add the baryonic acoustic oscillation (BAO) peak detected by large-scale correlation function of luminous red galaxies from Sloan Digital Sky Survey (SDSS) [Eisenstein et al. 2005], the cosmic microwave background (CMB) detected by the 7-year WMAP data [Komatsu et al. 2010] and the newly revised Union2 SNe Ia data set [Amanullah et al. 2010]. This paper is organized as follows: In section 2, we introduce the observational data including the $H(z)$, BAO, CMB and SNe Ia data. In section 3, we derive two Hubble parameters and perform a Markov Chain Monte Carlo analysis spanning the full parameter space of the model using different data sets. Finally, we summarize the main conclusions in Section 4.

2. Observational data

In this section we will list the cosmological observations used in our calculations: $H(z)$, BAO, CMB as well as the SNe Ia observations. We adopt the $H(z)$ data at 11 different redshifts obtained in Ref. Stern et al. (2010), and two $H(z)$ data ($H(z = 0.24) = 76.69 \pm 2.32$, and $H(z = 0.43) = 86.45 \pm 3.27$) determined by Gaztañaga et al. (2009). The corresponding $\chi^2$ can be defined as

$$\chi^2_H = \sum_{i=1}^{13} \left[ \frac{H(z_i) - H_{\text{obs}}(z_i)}{\sigma_{hi}} \right]^2,$$

where $\sigma_{hi}$ is the 1σ uncertainty in the $H(z)$ data.

As is known, the baryonic oscillations at recombination are expected to leave baryonic acoustic oscillations (BAO) in the power spectrum of galaxies. The expected BAO scale depends on the scale of the sound horizon at recombination, and on transverse and radial scales at the mean redshift $z_{BAO} = 0.35$ of galaxies in the survey. [Eisenstein et al. 2005] measured the quantity

$$A = \frac{\sqrt{\Omega_m}}{E(z_{BAO})^{1/3}} \left[ \frac{1}{z_{BAO}} \int_0^{z_{BAO}} \frac{dz}{E(z')} \right]^{2/3},$$

The SDSS BAO measurement [Eisenstein et al. 2005] gives $A_{\text{obs}} = 0.469(n_s/0.98) - 0.35 \pm 0.017$ where the scalar spectral index is taken to be $n_s = 0.963$ as measured by WMAP7 [Komatsu et al. 2010]. In this case, $\chi^2$ can be defined as

$$\chi^2_{BAO} = \frac{(A - A_{\text{obs}})^2}{\sigma_A^2}.$$
Meanwhile, the locations of peaks in the CMB temperature power spectrum in l-space depend on the comoving scale of the sound horizon at recombination, and the angular distance to recombination. This is summarized by the so-called CMB shift parameter $R$ (Bond et al. 1997; Wang & Mukherjee 2006) which is related to the cosmology by

$$R = \sqrt{\Omega_m} \int_0^{z_{rec}} \frac{dz'}{E(z')}$$

(7)

where $z_{rec} \approx 1091.3$ (Komatsu et al. 2010) is the redshift of recombination. The 7-year WMAP data gives a shift parameter $R = 1.725 \pm 0.018$ (Komatsu et al. 2010). In this case, $\chi^2$ can be defined as

$$\chi^2_{\text{CMB}} = \frac{(R - R_{\text{obs}})^2}{\sigma_R^2}$$

(8)

Notice that both $A$ and $R$ are independent of $H_0$, thus these quantities can provide robust constraint as complement to $H(z)$ on dark energy models.

It is commonly believed that SNe Ia all have the same intrinsic luminosity, and thus can be used as “standard candles.” Recently, the Supernova Cosmology Project (SCP) collaboration have released their Union2 compilation which consists of 557 SNe Ia (Amanullah et al. 2010). The Union2 compilation is the largest published and spectroscopically confirmed SNe Ia sample to date, which are used in this paper. In the calculation of the likelihood from SNe Ia we have marginalized over the nuisance parameter (Di Pietro & Claeskens 2003):

$$\chi^2_{\text{SN}} = A - \frac{B^2}{C} + \ln \left( \frac{C}{2\pi} \right),$$

(9)

where $A = \sum_{i=1}^{557} \frac{(\mu_{\text{data}} - \mu_{\text{th}})^2}{\sigma_i^2}$, $B = \sum_{i=1}^{557} \mu_{\text{data}} - \mu_{\text{th}}/\sigma_i^2$, $C = \sum_{i=1}^{557} 1/\sigma_i^2$, $\mu_{\text{data}}$ is the distance modulus obtained from observations and $\sigma_i$ is the total uncertainty of SNe Ia data.

### 3. Constraint on the IDE models

The model parameters are determined by applying the maximum likelihood method of $\chi^2$ fit by using the Markov Chain Monte Carlo (MCMC) method. We minimize $\chi^2$ to determine the best-fit parameters and our method is based on cosmoMC (Lewis & Bridle 2002). Basically, The model parameters are determined by minimizing

$$\chi^2 = \chi^2_H + \chi^2_{\text{BAO}} + \chi^2_{\text{CMB}} + \chi^2_{\text{SN}}.$$
3.1. The $\gamma_m$ IDE Model

If the interaction term is $Q = 3\gamma_m H\rho_m$, in spatially flat FRW metric, for the the $\gamma_m$ IDE model with a constant EoS of dark energy $w_X$, the Friedmann equation is

$$E^2(z) = \frac{w_X \Omega_{m0}}{\gamma_m + w_X} (1 + z)^{3(1-\gamma_m)} + \left(1 - \frac{w_X \Omega_{m0}}{\gamma_m + w_X}\right)(1 + z)^{3(1+w_X)}.$$ (11)

The joint confidence regions in $w_X$-$\gamma_m$ plane with different observational data sets ($H(z)$, $H(z)$+BAO+CMB, SNe Ia+BAO+CMB, and $H(z)$+SNe Ia+BAO+CMB) for the $\gamma_m$ IDE model model are showed in Fig. 1. We also present the best-fit values of parameters with 1-$\sigma$ and 2-$\sigma$ uncertainties in Table 1. With the $H(z)$ data only (Fig. 1a), the best-fit values of the parameters ($w_X$, $\gamma_m$) are $w_X = -2.79$ and $\gamma_m = 0.22$. With $H(z)$+BAO+CMB (Fig. 1b), the best-fit values at 1-$\sigma$ are $w_X = -1.10^{+0.16}_{-0.17}$, $\gamma_m = -0.013^{+0.013}_{-0.011}$. For comparison, fitting results from the joint data with SNe Ia+BAO+CMB are given in Fig. 1c. with the best-fit values $w_X = -1.02^{+0.12}_{-0.13}$ and $\gamma_m = -0.009^{+0.013}_{-0.012}$. In Fig. 1d, we show the fitting results from the joint data with $H(z)$+SNe Ia+BAO+CMB, with the best-fit values $w_X = -1.05^{+0.11}_{-0.12}$ and $\gamma_m = -0.011^{+0.012}_{-0.011}$.

It is obvious that $H(z)$ only gives a relatively weak constraint on all of the relevant model parameters. We find that the $H(z)$ data, when combined to CMB and BAO observations, can give more stringent constraints on this phenomenological interacting scenario. Moreover, the special case ($\gamma_m = 0, w_X = -1$, corresponding to the $\Lambda$CDM with no interaction) is excluded at 1$\sigma$ for $H(z)$+BAO+CMB. However, obviously, with the two joint analyses including the SNe Ia data, $\Lambda$CDM is still included within 1$\sigma$ error region. Moreover, comparing Fig. 1b to Fig. 1c, we can find the confidence regions of $H(z)$+BAO+CMB data are in good agreement with that of SNe Ia+BAO+CMB data; this situation has also been noted when constraining on the $\Lambda$CDM, XCDM scenario (Zhai et al. 2010) and the interacting dark matter models without dark energy (Cao, Zhu & Liang 2011).

3.2. The $\gamma_d$ IDE Model

If the interaction term is $Q = 3\gamma_d H\rho_X$, in spatially flat FRW metric, for the the $\gamma_d$ IDE model with a constant EoS of dark energy $w_X$, the Friedmann equation is

$$E^2(z) = (1 - \Omega_{m0})(1 + z)^{3(1+\gamma_d+w_X)} + \left(1 + z\right)^{3\frac{w_X \Omega_{m0} + \gamma_d + \gamma_d(\Omega_{m0} - 1)(1 + z)^{3(\gamma_d+w_X)}}{w_X + \gamma_d}}.$$ (12)
Fig. 1.— The 68.3% and 95.4% confidence level contours for $w_X$ versus $\gamma_m$ with the $H(z)$ data (a); $H(z)$+BAO+CMB (b); SNeIa+BAO+CMB (c); $H(z)$+SNeIa+BAO+CMB (d). The dashed lines represent $\gamma_m = 0$ and $w_X = -1$. 
The joint confidence regions in $w_X-\gamma_d$ plane with different observational data sets ($H(z)$, $H(z)$+BAO+CMB, SNe Ia+BAO+CMB, and $H(z)$+SNe Ia+BAO+CMB) for the $\gamma_d$ IDE model are showed in Fig. 2. We also present the best-fit values of parameters with 1-$\sigma$ and 2-$\sigma$ uncertainties for the $\gamma_d$ IDE model in Table II. With the $H(z)$ data only (Fig. 2a), the best-fit values of the parameters ($w_X, \gamma_d$) are $w_X = -1.30$ and $\gamma_d = -0.057$. With $H(z)$+BAO+CMB (Fig. 2b), the best-fit values at 1-$\sigma$ confidence level are ($w_X, \gamma_d$) = ($-1.24^{+0.17}_{-0.19}, -0.040^{+0.042}_{-0.042}$). Fitting results from the joint data with SNe Ia+BAO+CMB are given in Fig. 2c with the best-fit values ($w_X, \gamma_d$) = ($-1.02^{+0.09}_{-0.09}, -0.023^{+0.039}_{-0.040}$). Though the special case of the $\Lambda$CDM with no interaction is excluded at 1$\sigma$ for $H(z)$+BAO+CMB. Fitting results from the joint data with $H(z)$+SNe Ia+BAO+CMB given in Fig. 2d with the best-fit values ($w_X, \gamma_d$) = ($-1.10^{+0.13}_{-0.13}, -0.036^{+0.037}_{-0.037}$) indicate that $\Lambda$CDM is still included within 1$\sigma$ error region.

From Fig. 1-2 and Table II it is obvious that the constraints on both interacting scenarios favor $\gamma < 0$, which indicates that the energy is transferred from dark matter to dark energy and the coincidence problem is quite severe, a result consistent with the previous results by using other observational data including the 182 Gold SNe Ia and 397 Constitution SNe Ia samples (Chen et al. 2010; Feng et al. 2007). In addition, the constraining results in this work with the joint observational data including the $H(z)$ data are more stringent than the previous results for constraining the interaction term with other combined observations arising from the 182 Gold SNe Ia samples, the shift parameter of CMB given by the 3-year WMAP observations, the BAO measurement from SDSS and age estimates of 35 galaxies (Feng et al. 2008).

4. Conclusions

In this paper, we have examined, with the newly revised $H(z)$ versus redshift data, as well as the baryonic acoustic oscillation (BAO) peak detected by large-scale correlation function of luminous red galaxies from Sloan Digital Sky Survey (SDSS), the cosmic microwave background (CMB) observation and the 557 newly released Union2 SNe Ia data, to constrain two phenomenological interaction models for dark energy and dark matter, which are proposed as candidates to ease the coincidence problem of the concordance $\Lambda$CDM model. We find that, for the $\gamma_m$ IDE and $\gamma_d$ IDE models where $\gamma_m$ and $\gamma_d$ quantify the extent of interaction, although the $H(z)$ data can not tightly constrain the model parameters, stringent constraints can be obtained in combination with the CMB observation from the WMAP7 results, the BAO observation from the SDSS Data Release and the Union2 SNeIa set. In order to examine the role of the $H(z)$ data played in cosmological constraints, we also compare the SNe
Fig. 2.— The 68.3% and 95.4% confidence level contours for $w_X$ versus $\gamma_d$ with the $H(z)$ data (a); $H(z)$+BAO+CMB (b); SNeIa+BAO+CMB (c); $H(z)$+SNeIa+BAO+CMB (d). The dashed lines represent $\gamma_d = 0$ and $w_X = -1$. 
Ia data in the same way and find the constraints with $H(z)$+BAO+CMB, SNe+BAO+CMB, and $H(z)$+SNe+BAO+CMB combinations are consistent with each other.

For the $\gamma_m$ IDE model, we obtain $w_X = -1.10^{\pm0.16}_{-0.17}$, $\gamma_m = -0.013^{+0.013}_{-0.011}$ with $H(z)$+BAO+CMB, which shows that the special case ($\gamma_m = 0, w_X = -1$, corresponding to the ΛCDM with no interaction) is excluded at 1σ; whereas for SNe Ia+BAO+CMB and $H(z)$+SNe Ia+BAO+CMB, the best-fit values are $\gamma_m = -0.009^{+0.013}_{-0.012}$ and $\gamma_m = -0.011^{+0.012}_{-0.011}$, which indicates that the ΛCDM model is still included within 1σ error region. For the $\gamma_d$ IDE model, with $H(z)$+BAO+CMB, the best-fit values are $(w_X, \gamma_d) = (-1.24^{+0.17}_{-0.19}, -0.604^{+0.042}_{-0.040})$ and the special case ($\gamma_d = 0, w_X = -1$) is excluded at 1σ. However, with SNe Ia+BAO+CMB and $H(z)$+SNe Ia+BAO+CMB, the best-fit values are $\gamma_d = -0.023^{+0.039}_{-0.040}$ and $\gamma_d = -0.030^{+0.037}_{-0.037}$, respectively. The ΛCDM model is still included within 1σ error region. These results are more stringent and consistent with the previous constraint results (Guo et al. 2007; Feng et al. 2008; Chen et al. 2010).

In summary, our results show that the concordance ΛCDM model still remains to be a good fit to the recent observational data. However, the interaction that the energy transferring from dark matter to dark energy is slightly favoured over the interaction delivering energy from dark energy to dark matter, which is consistent with those obtained by Guo et al. (2007); Feng et al. (2008); Chen et al. (2010), therefore, the coincidence problem is quite severe in the two phenomenological scenarios. We are looking forwards to see whether these results may be changed with future observational data of high redshift SNe Ia data from SNAP etc (Abraham et al. 2004), more precise CMB data from the ESA Planck satellite (Balbi 2007), as well as other complementary data, such as Gamma Ray Bursts data (Schaefer 2007; Basilakos & Perivolaropoulos 2008; Liang et al. 2008; Liang, Xu & Zhu 2010; Gao et al. 2010; Wang & Liang 2010), the data of X-ray gas mass fraction in clusters (Allen et al. 2004, 2008; Ettori et al. 2009) and gravitational lensing data (Zhu 1998; Sereno 2002; Cao & Zhu 2011).

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Table 1: The best-fit value of parameters \{Ω_{m,0}, w_X, γ_m (γ_d)\} for the γ_m IDE, γ_d IDE with 1-σ and 2-σ uncertainty for \(H(z)+\text{BAO+CMB}\), SNe Ia+BAO+CMB and \(H(z)+\text{SNe Ia+BAO+CMB}\), respectively.