Constraining interacting dark energy models with latest cosmological observations

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ABSTRACT
The local measurement of \(H_0\) is in tension with the prediction of ΛCDM model based on the Planck data. This tension may imply that dark energy is strengthened in the late-time Universe. We employ the latest cosmological observations on CMB, BAO, LSS, SNe, \(H(z)\) and \(H_0\) to constrain several interacting dark energy models. Our results show no significant indications for the interaction between dark energy and dark matter. The \(H_0\) tension can be moderately alleviated, but not totally released.

Key words: dark energy; cosmological parameters

1 INTRODUCTION
The Hubble parameter \(H\) brings important information of our Universe. It is dynamically determined by the Friedmann equations, and then evolves with cosmological redshift. The evolution of Hubble parameter is closely related with the cosmic inventories, including radiations, baryon, cold dark matter, and dark energy, or even other exotic components in the Universe. Further, it may be impacted by some interactions between these inventories. Thus one can spy upon the evolution of the Universe by measuring the Hubble parameter. Measuring \(H_0\) could give a stringent test of the standard cosmological model, or provide evidence for some new physics beyond the standard model.

The Hubble constant \(H_0\), today’s Hubble parameter with redshift \(z = 0\), has been precisely measured by many approaches. For instance, the Planck Collaboration (Ade et al. 2015) have obtained a severe constraint on \(H_0\) by observing the cosmic microwave background (CMB) which is formed in a large redshift \(z \approx 10^9\). This constraint is given by \(H_0 = 67.27 \pm 0.66\) km/s/Mpc in the framework of base ΛCDM model. Here the 1σ uncertainty has been reduced to a 1% level. With 300 supernovae of type Ia (SNe Ia) at \(z < 0.15\), recently, the Hubble constant \(H_0\) has been locally determined to be 73.02 ± 1.79 km/s/Mpc by using the Wide Field Camera 3 (WFC3) on the Hubble Space Telescope (HST) (Riess et al. 2016). The 1σ uncertainty of \(H_0\) has been reduced from 3.3% to 2.4%. However, this value of local \(H_0\) measurement is 3σ higher than 67.27 ± 0.66 km/s/Mpc, which is predicted by the base ΛCDM model according to the Planck CMB data (Ade et al. 2015). In other words, there is a tension between these two measurements.

The \(H_0\) tension might imply some underlying new physics, if it does not arise from some unknown systematic uncertainties. The CMB observations are sensitive to the physics at the last-scattering surface with redshift \(z \sim 10^3\). By contrast, the local \(H_0\) measurement is just sensitive to the late-time physics with redshift \(z < 0.15\). To resolve the \(H_0\) tension, one possible way is to introducing the interaction between cold dark matter and dark energy. The cold dark matter could be converted into the dark energy with the evolution of the Universe. Thus the dark energy will be strengthened in the late-time Universe, and then more efficiently drive the cosmic accelerating expansion. Actually, several papers (Salvatelli et al. 2014; Sola et al. 2015; 2016) have provided the first and strong indication of interaction in the dark sector recently.

In this paper, we will study several interacting dark energy (IDE) models by using the latest cosmological observations. Our data compilation include the distance priors, the baryon acoustic oscillation (BAO), the supernovae of type Ia (SNe), the large-scale structure (LSS), the Hubble parameter \(H(z)\), and the local \(H_0\) measurement. The distance priors were subtracted by Huang, Wang & Wang (2015) with the Planck CMB data released in 2015. The BAO data include 6dFGS (Beutler et al. 2011), SDSS MGS (Ross et al. 2015), and WiggleZ (Kazin et al. 2014). The LSS data include the anisotropic clustering of LOWZ and CMASS galaxies (Gil-Marin et al. 2016). The SNe data refers to the “Joint Lightcurve Analysis” (JLA) compilation (Betoule et al. 2014). The \(H(z)\) data include 30 data points which are obtained by the differential-age techniques applied to passively evolving galaxies (Zhang et al. 2014; Jimenez et al. 2003; Simon, Verde & Jimenez 2005; Stern et al. 2010).
2 INTERACTING DARK ENERGY MODELS

We consider the spatially flat Universe in this study. The Friedmann’s equation is given by $3M_0^2H^2 = \rho_{de} + \rho_c + p_c + \rho_b + \rho_r$, where $H = d \ln a/dt$ is the Hubble parameter, $M_0 = 1/\sqrt{8\pi G}$ denotes the reduced Planck mass, and $\rho_{de}$, $\rho_c$, $\rho_b$ and $\rho_r$ denote the energy densities of dark energy, cold dark matter, baryon, and radiations, respectively. We can define the dimensionless Hubble parameter $E(z) = H(z)/H_0$, which satisfies

$$E^2 = \Omega_{de0} \frac{\rho_{de}}{\rho_{c0}} + \Omega_{c0} \frac{\rho_c}{\rho_{c0}} + \Omega_{b0} \frac{\rho_b}{\rho_{c0}} + \Omega_{r0} \frac{\rho_r}{\rho_{c0}},$$

where $\Omega_{de0}$, $\Omega_{c0}$, $\Omega_{b0}$ and $\Omega_{r0}$ denote today’s energy-density fractions of dark energy, cold dark matter, baryon and radiations, respectively. We have $\rho_0 = \rho_{c0}(1 + z)^3$, and $\rho_r = \rho_{r0}(1 + z)^4$. Once the equation of state ($w$) of dark energy and the interaction between dark sectors are assumed, $\rho_{de}$ and $\rho_c$ can be also expressed in terms of $z$. In addition, we have $\Omega_{c0} = \Omega_{c0}(1 + 0.2271N_{eff})$ where $\Omega_{c0} = 2.469 \times 10^{-5} h^{-2}$, $N_{eff} = 3.046$, and $H_0 = 100h$ km/s/Mpc. Thus the free parameters are $H_0$, $\Omega_{c0}$, $\Omega_{b0}$, $w$, and an interaction parameter. One should note that $\Omega_{de0}$ is a derived parameter, since we have a relation $\Omega_{de0} + \Omega_{m0} + \Omega_{r0} = 1$. Here we denote $\Omega_{m0} = \Omega_{c0} + \Omega_{b0}$.

We consider the interaction between dark energy and cold dark matter. The dynamical equations of dark energy and cold dark matter are given by

$$\frac{d\rho_{de}}{dt} + 3H(\rho_{de} + p_{de}) = -Q,$$

$$\frac{d\rho_c}{dt} + 3H\rho_c = Q,$$

where $Q$ denotes an interaction term. The above two equations can be rewritten as

$$(1 + z)\frac{d\rho_{de}}{dz} - 3(1 + w)\rho_{de} = \frac{Q}{H},$$

$$(1 + z)\frac{d\rho_c}{dz} - 3\rho_c = -\frac{Q}{H},$$

where we have used the equation of state of dark energy, i.e. $w = p/\rho$, and noticed relations $z = a^{-1} - 1$ and $d/a = -H(1 + z)/dH$. The interaction term $Q$ determines the energy transfer rate between dark energy and cold dark matter. However, its specific form is still an open question. One should assume certain possible forms of $Q$ to study the issue of interaction between dark sectors. The following three forms were usually considered, see (Amendola et al. 2007; Guo, Ohta & Tsujikawa 2007; Zhang, Liu & Zhang 2008; Costa et al. 2016) and references therein. They are given by

$$Q_0 = 0,$$

$$Q_1 = 3\gamma H\rho_{de},$$

$$Q_2 = 3\gamma H\rho_c,$$

where $\gamma$ denotes a dimensionless coupling parameter. One should note that the model with $Q_0$ denotes no interaction between dark sectors. Usually, the above three models are denoted by $wCDM$ model, $IwCDM1$ model and $IwCDM2$ model, respectively. Particularly, we are interested in some one-parameter generalizations of $\Lambda CDM$ model. We will study the IDE models with $w = -1$, which are called IACDM1 model and IACDM2 model, respectively.

Once the interaction term $Q$ is determined, one can solve (4) and (5) to finally obtain $E(z)$ in (1). For the $wCDM$ model, we deduce $E(z)$ of the form

$$E^2(z) = \Omega_{de0}(1 + z)^{3(1+w)} + \Omega_{m0}(1 + z)^3 + \Omega_{r0}(1 + z)^4,$$

since there is no interaction between dark sectors. In the case of $w = -1$, we recover the $\Lambda CDM$ model. For the $IwCDM1$ model, we deduce $E(z)$ of the form

$$E^2(z) = \Omega_{de0}\left(\frac{\omega_{de}}{\omega_{T}}(1 + z)^3 + \frac{w}{\omega_{T}}(1 + z)^{3(1+w)}\right) + \Omega_{m0}(1 + z)^3 + \Omega_{r0}(1 + z)^4,$$

since (4) has a solution $\rho_{de} = \rho_{c0}(1 + z)^{3(1+w)}$. For the $IwCDM2$ model, we deduce $E(z)$ of the form

$$E^2(z) = \Omega_{de0}(1 + z)^{3(1+w)} + \Omega_{m0}(1 + z)^3 + \Omega_{r0}(1 + z)^4 + \Omega_{r0}\left(\frac{\omega_{de}}{\omega_{T}}(1 + z)^{3(1+w)} + \frac{w}{\omega_{T}}(1 + z)^{3(1+w)}\right),$$

since (5) has a solution $\rho_c = \rho_{c0}(1 + z)^{3(1-w)}$. One should let $w = -1$ in the above two expressions, if he wants to study $I\Lambda CDM1$ model and $I\Lambda CDM2$ model.

3 DATA AND METHODOLOGY

In this study, we will use the latest CMB, BAO and $H_0$ data to constrain the IDE coupling parameter $\gamma$ together with other cosmological parameters. Both the physics of CMB and BAO are well understood, and the systematic uncertainties are under control. Recently, the local value of the Hubble constant $H_0$ has been determined to 2.4% level. However, this value has tension with the prediction of $\Lambda CDM$ model which is based on the CMB observations. In this paper, we will show that this tension will disappear in some IDE models. In other words, the $H_0$ data, combined with CMB and BAO, will give a good constraint on the IDE coupling parameter $\gamma$.

For the CMB data, we use the distance priors which are obtained from the Planck data release 2015. One denotes the comoving distance to the last-scattering surface by $r(z_s)$, and the comoving sound horizon at the last-scattering epoch by $r_s(z_s)$. Then the distance priors are given by these two distance scales through $\ell_A = \pi r(z_s)/r_s(z_s)$ and $R = r(z_s)/\Omega_{m0}H_0^2$ (Bond, Efstathiou & Tegmark 1997; Efstathiou & Bond 1998; Wang & Mukherjee 2007), where $z_s$ denotes the redshift at the last-scattering surface. Combined with the physical baryon fraction $\omega_b = \Omega_{b0}h^2$, they summarize the CMB data very...
Here the comoving distance to the redshift $z$ is defined by $r(z) = H_0^{-1} \int_0^z \frac{dz'}{H(z')}$, for the spatially flat Universe. The comoving sound horizon to the last-scattering surface is given by $r_s(z_s) = H_0^{-1} \int_0^{z_s} \frac{dz}{H(z)}$, and $r$ is the redshift and the heliocentric redshift, respectively. The distance modulus is defined as $\mu = 5 \log_{10}(D_L/10\text{pc})$. The $\chi^2_{SN}$ of the JLA SNe is given by $\chi^2_{SN} = (\mu_{obs} - \mu_{th})^2 / \sigma^2_{\mu}$, where $\sigma_{\mu}$ is a covariance matrix.

For the H(z) data, we use 30 data points listed in Table 2. They are obtained by the differential-age techniques applied to passively evolving galaxies (Zhang et al. 2014; Jimenez et al. 2003; Simon, Verde & Jimenez 2005; Stern et al. 2010; Moresco et al. 2012). The data list of the observed Hubble parameters $H(z)$ [km s$^{-1}$ Mpc$^{-1}$] is given below.

$$H(z) = \frac{dz}{dt} = \frac{H_0}{r_s(z)} \sqrt{\Omega_m (1 + z)^3 + \Omega_{\Lambda}}.$$
tions. For example, it is $3.0\sigma$ higher than the $67.27 \pm 0.66$ km s$^{-1}$ Mpc$^{-1}$ which is predicted by the base $\Lambda$CDM model and Planck CMB data (Ade et al. 2015). In this study, we try to resolve this tension in the framework of IDE models. The $\chi^2_{H_0}$ of the local $H_0$ data is given by

$$\chi^2_{H_0} = \left( \frac{H_0 - b^{obs}_{H_0}}{\sigma_{H_0}} \right)^2,$$

where $\sigma_{H_0}$ denotes the $1\sigma$ uncertainty of local $H_0$, and $b^{obs}_{H_0}$ is the mean value of local $H_0$. The distance priors are sensitive to the physics with the redshift $z \sim 10^3$. By contrast, the $H_0$ observation is corresponded to the late-time physics $z < 0.15$. In other words, a higher value of local $H_0$ may reveal that the dark energy is strengthened in the late-time Universe.

We employ the Cosmological Monte Carlo (CosmoMC) sampler (Lewis & Bridle 2002) to estimate the parameter space of the IDE models. The Gelman and Rubin criterion is set by $R - 1 = 0.01$ to ensure the statistical convergence. We use the data combination CMB+BAO+SNe+LSS+$H(z)+H_0$ in this study. The joint likelihood is given by $L \propto e^{-\chi^2/2}$, where $\chi^2 = \chi^2_{CMB} + \chi^2_{BAO} + \chi^2_{SNe} + \chi^2_{LSS} + \chi^2_{H(z)} + \chi^2_{H_0}$. For the wCDM model, the parameter space is spanned by $\{H_0, \Omega_0, \Omega_b, H_0, w\}$. For the IwCDM model, the parameter space is spanned by $\{H_0, \Omega_0, \Omega_b, H_0, w, \gamma\}$. Here $\Omega_0$ is a derived parameter. In addition, we also consider the IACDM models for which $w = -1$, and the parameter spanned by $\{\Omega_0, \Omega_b, H_0, \gamma\}$. One should note that $\Omega_0$ is a derived parameter.

We employ the Deviance Information Criterion (DIC) to judge either a model $M_1$ or a model $M_2$ is preferred by a given data set $D$. To describe the goodness of fit, as mentioned above, we calculate $\chi^2 = \chi^2(p) = -2\ln L(D|p, M_i)$ where $p$ denotes a set of parameters of the model $M_i$. The mean goodness of fit is given by $\langle \chi^2 \rangle = -2\ln L$. Spiegelhalter et al. (2002) define the DIC as $\text{DIC}(M_i) = \langle \chi^2 \rangle + p_D$, where $p_D$ denotes the Bayesian complexity describing the effective complexity of the model. The Bayesian complexity is defined by $p_D = (\chi^2 - \chi^2(p))$, where $p$ is the maximum likelihood point in the parameter space. A lower DIC implies either the model fits the data better (a lower $\chi^2$) or the model has less complexity. We refer to the difference between the DICs of two models, namely, $\Delta \text{DIC} = \text{DIC}(M_1) - \text{DIC}(M_2)$. If $\Delta \text{DIC} = 0$, neither model is preferred by the data. If $0 < \Delta \text{DIC} < 2$, the data indicates no significant preference for $M_2$. If $2 < \Delta \text{DIC} < 6$, there is a positive preference for $M_2$. If $\Delta \text{DIC} > 6$, the preference is strong. By contrast, the negative values mean that the data prefers $M_1$.

4 RESULTS

Our constraints on cosmological parameters are summarized in Table 3 for the $\Lambda$CDM model and two IACDM models. For the $\Lambda$CDM model, the best-fit value of $H_0$, i.e. $H_0 = 68.75 \pm 0.49$ km s$^{-1}$ Mpc$^{-1}$, is much lower than the local value of $H_0$ by $2.4\sigma$. Similar situations are showed for both IACDM models. The dimensionless coupling parameter $\gamma$ is consistent with zero for both IACDM models. By contrast to the ACDM model, the data combination prefer neither the IACDM1 model nor the IACDM2 model. For both IACDM models, the minimum $\chi^2$ are similar to that of the ACDM model, but their DIC are larger than that of the ACDM model. The data combination show a preference for the ACDM model.

Our constraints on cosmological parameters are summarized in Table 4 for the wCDM model and two IwCDM models. The data combination prefers $w < -1$ at the $1.4\sigma$ level, namely, we have $w = -1.055 \pm 0.039$. However, the best-fit value of $H_0$, i.e. $H_0 = 69.88 \pm 0.90$ km s$^{-1}$/Mpc, is still lower than the local value of $H_0$ by $1.75\sigma$. By contrast to the ACDM model, the $H_0$ tension is slightly alleviated in the wCDM model, but not enough. Based on $\Delta \text{DIC} = \text{DIC}_{wCDM} - \text{DIC}_{ACDM} = -0.93$, we find that there is no significant preference for the wCDM model. In addition, the wCDM model fits the data better than the ACDM model, since the minimum $\chi^2$ is reduced by $1.88$.

By contrast to the wCDM model, the $H_0$ tension is still remained in the IwCDM1 model, even though we consider the interaction effect between the dark sector. We obtain $H_0 = 69.87 \pm 0.98$ km s$^{-1}$/Mpc which is lower than the local $H_0$ measurement by $1.76\sigma$. The best-fit value of $w$, i.e. $w = -1.064 \pm 0.053$, is also smaller than $-1$ at the $1.2\sigma$ level. The dimensionless coupling parameter, i.e. $\gamma = -0.0014 \pm 0.0051$, is consistent with zero. In this model, the minimum $\chi^2$ is
smaller by 1.71 than that of the ΛCDM model. However, the DIC becomes larger by 1.62. Thus this model is not significantly preferred by the data, even though it fits the data better.

For the IwCDM2 model, the best-fit value of $H_0$, i.e. $H_0 = 70.65 \pm 1.15$ km/s/Mpc, is lower than the local $H_0$ measurement by 1.3σ. The $H_0$ tension is moderately alleviated in this model. The best-fit value of $w$, i.e. $w = 0.96 \pm 0.015$, is smaller than $-1$ by around 1.9σ. The dimensionless coupling parameter, i.e. $\gamma = -0.0015 \pm 0.0016$, which is consistent with zero within 1σ. By contrast to the ΛCDM model, the $\chi^2$ for the IwCDM2 model becomes smaller by 2.74. Since the DIC becomes larger by 0.36, there is no significant preference for the IwCDM2 model.

To directly show how the wCDM model alleviates the $H_0$ tension, we plot the marginalized distribution contour of $H_0$ and $w$ in Figure 1. We find that $H_0$ is strongly anti-correlated with $w$ in the $H_0$-$w$ plane. Thus a higher value of $H_0$ can be accounted by a smaller value of $w$. To reveal how the local $H_0$ data constrains the IwCDM models, we plot the marginalized distribution contours and the likelihood distributions of $H_0$, $w$, and $\gamma$ in Figure 2. Similar to the wCDM model, $H_0$ is also anti-correlated with $w$ in both IwCDM models. It is further anti-correlated with $\gamma$. This means that a higher value of $H_0$ requires more energy density flowing from cold dark matter to dark energy. Unfortunately, both IwCDM models can not totally resolve the $H_0$ tension, but just alleviate.

Our above results can be compared with recent results obtained by other authors. For instance, Costa et al. (2016) made updated constraints for IwCDM1 and IwCDM2 by using the Planck+BAO+SNIa+RSD+$H_0$ data. In this paragraph, Planck denotes Planck 2015 CMB data instead of the distance priors; BAO denotes the isotropic 6dFGS, MGS, BOSS DR11 LOWZ and CMASS; the value of $H_0$ is lower than the report of Riess et al. (2016). The authors found that the interaction between dark sectors strongly suppressed. This is compatible with our result in this study. Murgia.

5 CONCLUSION

The cosmological observations have provided us highly precise data. Recently, the local measurement showed a higher value of $H_0$ than the prediction of ΛCDM model based on the CMB data. This fact might reveal either some tensions exist between the local $H_0$ measurement and the CMB observations, or there is underlying new physics. For example, dark energy may be strengthened in the late-time Universe. In this paper, we explored several IDE models with the latest cosmological observations including the data of CMB, BAO, LSS, SNe, $H(z)$ and $H_0$. In the IDE models, the interaction between dark sectors may strengthen dark energy. This fact could help to reconcile the $H_0$ tension.

Our results showed that the local value of $H_0$ is still in tension with two IACDM models considered in this study. However, the wCDM model can slightly alleviate this tension. The higher value of local $H_0$ implies a more negative value of $w$. We obtained $w = -1.055 \pm 0.039$ in this case. The interaction between dark sectors could further re-
lease the $H_0$ tension. The data combination provided severe constraints on the interacting coupling parameter $\gamma$ in two IwCDM models. We obtained $w = -1.064 \pm 0.053$ and $\gamma = -0.0014 \pm 0.0051$ for the IwCDM1 model, and $w = -1.071 \pm 0.043$ and $\gamma = -0.0015 \pm 0.0016$ for the IwCDM2 model. Therefore, we found no significant preference for the interaction between dark energy and dark matter.

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