Observational constraints on the interacting Ricci dark energy model

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Abstract

We consider an extension of the holographic Ricci dark energy model by introducing an interaction between dark energy and matter. In this model, the dark energy density is given by \( \rho_\Lambda = -\frac{1}{2} \alpha M_p^2 R \), where \( R \) is the Ricci scalar curvature, \( M_p \) is the reduced Planck mass, and \( \alpha \) is a dimensionless parameter. The interaction rate is given by \( Q = \gamma H \rho_\Lambda \), where \( H \) is the Hubble expansion rate, and \( \gamma \) is a dimensionless parameter. We investigate current observational constraints on this model by applying the type Ia supernovae, the baryon acoustic oscillation and the CMB anisotropy data. It is shown that a nonvanishing interaction rate is favored by the observations. The best fit values are \( \alpha = 0.45 \pm 0.03 \) and \( \gamma = 0.15 \pm 0.03 \) for the present dark energy density parameter \( \Omega_\Lambda_0 = 0.73 \pm 0.03 \).

1 Introduction

Recent observations of type Ia supernovae (SNIa) have revealed that the present Universe is undergoing accelerated expansion \cite{1}. This indicates that the energy density of the Universe at present epoch is dominated by dark energy with equation of state \( w_\Lambda = \frac{p_\Lambda}{\rho_\Lambda} < -\frac{1}{3} \), where \( \rho_\Lambda \) is the energy density of dark energy, and \( p_\Lambda \) is its pressure. Combining with observations of CMB anisotropy \cite{2} and the baryon acoustic oscillation (BAO) \cite{3}, the density parameter is determined as \( \Omega_\Lambda_0 = \rho_\Lambda_0 / \rho_c_0 \sim 0.7 \), where \( \rho_c_0 = 8.0992 h^2 \times 10^{-47} \text{GeV}^4 \) is the critical density today and \( H_0 = 100 h \text{ km/s/Mpc} \) is the present Hubble parameter.

The simplest way to explain dark energy is to introduce a cosmological constant \cite{4}. However, this model suffers from two problems \cite{5}. The first one is the fine-tuning problem: the observed cosmological constant is extremely small compared to the fundamental Planck scale \( \rho_\Lambda \sim 10^{-120} M_p^4 \), requiring an incredible fine-tuning. The second one is the cosmic coincidence problem: why the cosmological constant and matter have comparable

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energy density today even though their time evolution is so different. A variety of models have been proposed to solve these problems, such as quintessence \cite{6}, phantom \cite{7}, quintom \cite{8} and holographic dark energy \cite{9, 10, 11, 12}.

In particular, the holographic dark energy (HDE) models have been discussed extensively in recent years. These models are motivated by the holographic principle of quantum gravity \cite{13}. From the condition that a system with size $L$ would not form a black hole, it is required that the total vacuum energy should not exceed the mass of the black hole of the same size. Therefore, the dark energy density $\rho_\Lambda$ must satisfy $L^3 \rho_\Lambda \lesssim LM_p^2$ \cite{14}, where $M_p = 1/\sqrt{8\pi G}$ is the reduced Planck mass. Saturating this inequality, $\rho_\Lambda$ is defined by \cite{9}

$$\rho_\Lambda = 3c^2 M_p^2 L^{-2},$$

where $c$ is a dimensionless parameter. In Ref. \cite{14}, the size $L$, which is regarded as an IR cut-off, was chosen to be the inverse Hubble expansion rate $L \sim H^{-1}$ to naturally explain the observed vacuum energy density $\rho_{\Lambda 0} \sim 3M_p^2 H_0^2$. However, it was shown that this choice can not explain the accelerated expansion of the Universe at present \cite{15}. This problem was solved in Ref. \cite{9} by choosing $L$ to be the future event horizon $R_h$. Extensive studies on this model have been done, and the HDE model with the future event horizon as the IR cut-off is found to be consistent with current observational data \cite{16}. Various aspects on the HDE model have been discussed in Ref. \cite{17}. There have also been further developments on the HDE model by introducing an interaction between dark energy and matter \cite{18, 19}. However, it was pointed out that this model with $L = R_h$ has a conceptual problem that the future event horizon, which determines $\rho_\Lambda$, depends on the future evolution of the Universe, hence violates causality \cite{20}.

Subsequently, inspired by the HDE model, the holographic Ricci dark energy (RDE) model \cite{10} was proposed in which $\rho_\Lambda$ is proportional to the Ricci scalar curvature $\mathcal{R}$. It was shown that this model does not only avoid the causality problem and is phenomenologically viable, but also naturally solves the coincidence problem. Also, it was found that the causal connection scale $R_{CC}$ consistent with cosmological observations is given by $R_{CC}^2 = \dot{H} + 2H^2$ which is proportional to $\mathcal{R}$ in a flat universe \cite{21}. This may provide us with a physical motivation for the RDE model. Cosmological constraints on this model were studied in Ref. \cite{11}. Similar models have also been studied in Ref. \cite{12}.

In this paper, we consider the RDE model with an interaction between dark energy and matter, and call it the interacting Ricci dark energy (IRDE) model. We investigate the observational constraints on this model obtained from SNIa, CMB and BAO data. We organize this paper as follows. In section 2, we describe the IRDE model, and obtain analytic expressions for cosmic time evolution. In section 3, we discuss the observational constraints on this model. We summarize our results in section 4.

## 2 The interacting Ricci Dark Energy model

We consider the spatially homogeneous and isotropic Universe described by the Friedmann-Robertson-Walker metric

$$ds^2 = dt^2 - a^2(t) \left( \frac{dr^2}{1 - kr^2} + r^2 d\theta^2 + r^2 \sin^2 \theta d\phi^2 \right),$$

(2)
where \( k = 1, 0, -1 \) for closed, flat and open geometries. The time evolution of the scale factor \( a(t) \) is described by the Friedmann equation

\[
H^2 = \frac{1}{3M_p^2}(\rho_\Lambda + \rho_m + \rho_\gamma + \rho_k),
\]

(3)

where \( \rho_\Lambda, \rho_m, \rho_\gamma \) and \( \rho_k \) represent energy density of dark energy, matter, radiation and curvature, respectively, and \( H = \dot{a}/a \) is the Hubble parameter.

The energy density of dark energy in the IRDE model is defined as

\[
\rho_\Lambda = 3\alpha M_p^2 \left( \dot{H} + 2H^2 + \frac{k}{a^2} \right),
\]

(4)

where \( \alpha \) is a dimensionless parameter. Note that \( \rho_\Lambda \) is proportional to the Ricci scalar curvature

\[
\mathcal{R} = -6 \left( \dot{H} + 2H^2 + \frac{k}{a^2} \right).
\]

(5)

Moreover, it is assumed that there is an interaction between dark energy and matter. The energy densities \( \rho_\Lambda \) and \( \rho_m \) obey the following equations

\[
\dot{\rho}_\Lambda + 3H(1 + w_\Lambda)\rho_\Lambda = -Q,
\]

(6)

\[
\dot{\rho}_m + 3H\rho_m = Q.
\]

(7)

The interaction rate is given by

\[
Q = \gamma H \rho_\Lambda,
\]

(8)

where \( \gamma \) is a dimensionless parameter. The energy density of radiation is given by \( \rho_\gamma = \rho_{\gamma 0}a^{-4} \), where \( \rho_{\gamma 0} \) is the present value of radiation density. We adopt a convention that \( a(t_0) = 1 \) for the present age of the Universe \( t_0 \approx 14 \) Gyr. According to eq. (7) with \( Q \) in eq. (8), the interaction can be relevant if \( \gamma \rho_\Lambda \) and \( \rho_m \) are comparable, whether or not the Universe is in the radiation-dominated epoch. In literatures, various types of interactions between dark energy and matter have been considered, including \( Q = \gamma M_p^2 H^3 \), \( \gamma H \rho_\Lambda \), \( \gamma H \rho_m \), \( \gamma H(\rho_\Lambda + \rho_m) \), and so forth. At present, no definite mechanisms to determine the interaction are established. Thus, we simply assume eq. (8) as a phenomenological model.

Combining with eqs. (4) and (7), the Friedmann equation (3) is written as

\[
\frac{\alpha}{2} \frac{d^2H^2}{dx^2} - \left( 1 - \frac{7\alpha}{2} - \frac{\alpha\gamma}{2} \right) \frac{dH^2}{dx} - (3 - 6\alpha - 2\alpha\gamma)H^2
\]

\[
- \frac{\rho_{\gamma 0}}{3M_p^2}e^{-4x} - \{1 - \alpha(1 + \gamma)\}ke^{-2x} = 0,
\]

(9)

where \( x = \ln a \). The solution to eq. (9) is obtained as

\[
\frac{H^2}{H_0^2} = A_+e^{\sigma_+x} + A_-e^{\sigma_-x} + A_\gamma e^{-4x} + A_ke^{-2x},
\]

(10)

\[1\] If the interaction rate is given by \( Q = 9b^2M_p^2 H^3 \) \( (b^2 > 0) \) \[18\], it turns out that the matter density \( \rho_m \) becomes negative for \( a \ll 1 \). This problem does not occur for \( b^2 < 0 \). However, the case \( b^2 < 0 \) is disfavored by observational constraints.
where
\[
\sigma_{\pm} = \frac{2 - 7\alpha - \alpha\gamma \pm \sqrt{(2 - \alpha)^2 - 2\alpha(\alpha + 2)\gamma + \alpha^2\gamma^2}}{2\alpha},
\]  
(11)

\[\Omega_\gamma = \rho_\gamma/\rho_{c0}, \quad \Omega_k = -k/H_0^2\] and \[\rho_{c0} = 3M_p^2H_0^2\]. Note that \(\sigma_{\pm}\) can be imaginary for sufficiently large \(\alpha\) and \(\gamma\). This implies that there is a parameter region where \(H^2\) has oscillatory behavior. However, this region is not phenomenologically viable. The constants \(\Omega_\gamma\) and \(\Omega_k\) are the present value of \(\Omega_\gamma\) and \(\Omega_k\), respectively. The constants \(A_\gamma\), \(A_k\) and \(A_{\pm}\) are given by

\[
A_\gamma = \Omega_{\gamma 0},
\]  
(12)

\[
A_k = \Omega_{k0},
\]  
(13)

\[
A_{\pm} = \pm \frac{\alpha(\sigma_+ + 3)\Omega_{k0} + 2\Omega_{\Lambda 0} - \alpha(1 - \Omega_{\gamma 0})(\sigma_+ + 4)}{\alpha(\sigma_+ - \sigma_-)}.
\]  
(14)

Without the interaction \((\gamma = 0)\), eq. (10) reduces to the result obtained in the literature [10]. In this case, the constants in eq. (11) are \(\sigma_+ = -4 + 2/\alpha\) and \(\sigma_- = -3\).

Substituting eq. (10) to eq. (4), the Ricci dark energy density is given by

\[
\rho_\Lambda = \rho_{c0} \sum_{i=+, -} \alpha \left(\frac{\sigma_i}{2} + 2\right) A_i e^{\sigma_i x}.
\]  
(15)

Likewise, the matter density is

\[
\rho_m = \rho_{c0} \sum_{i=+, -} \left\{1 - \alpha \left(\frac{\sigma_i}{2} + 2\right)\right\} A_i e^{\sigma_i x}.
\]  
(16)

The equation of state of dark energy can be found by substituting eq. (15) into the following expression:

\[
w_\Lambda = -1 - \frac{1}{3} \left(\gamma + \frac{1}{\rho_\Lambda} \frac{d\rho_\Lambda}{dx}\right).
\]  
(17)

In eqs. (15) and (16), the term proportional to \(e^{\sigma_- x}\) is dominant in the past \(a \ll 1\), while the term proportional to \(e^{\sigma_+ x}\) is dominant in the future \(a \gg 1\). As an illustration, let us consider the case \(\alpha = 0.45\) and \(\gamma = 0.15\), which corresponds to \(\sigma_+ \approx 0.25\) and \(\sigma_- \approx -3.0\). In the past \(a \ll 1\), the ratio of eq. (16) to eq. (15) is \(\rho_m/\rho_\Lambda \approx \alpha^{-1}(\sigma_+ + 2)\), while \(\rho_m/\rho_\Lambda \approx \alpha^{-1}(\sigma_- + 2)\). In the future \(a \gg 1\), \(\rho_m/\rho_\Lambda \approx \alpha^{-1}(\sigma_+ + 2)\) is constant, while \(\rho_m/\rho_\Lambda \approx \alpha^{-1}(\sigma_- + 2)^{-1} - 1 \approx 0.045\), which is much smaller than in the past.

Notice that both \(\rho_\Lambda\) and \(\rho_m\) contribute non-standard time evolution. This typically leads to a constant ratio of \(\rho_\Lambda\) to \(\rho_m\), and it may help to solve the coincidence problem. As pointed out in Ref. [10], the coincidence problem is ameliorated in the original RDE model without interaction where \(\rho_\Lambda\) and \(\rho_m\) were comparable with each other in the past universe. In this case, \(\rho_\Lambda\) starts to increase at low redshift, and the ratio \(\rho_\Lambda/\rho_m\) rapidly grows in the future, since \(\rho_m \sim e^{-3x}\) in the absence of interaction. On the other hand, in the IRDE model, the behavior in the past is similar to that in the original RDE model, but the ratio \(\rho_\Lambda/\rho_m\) is constant even in the future.
3 Observational constraints

In this section, we study the cosmological constraints on the IRDE model obtained from SNIa, CMB and BAO observations. In what follows, we focus only on the spatially flat Universe ($k = 0$).

The SNIa observations measure the distance modulus $\mu$ of a supernova and its redshift $z$. The distance modulus is defined by

$$\mu = 5 \log_{10} \frac{d_L}{\text{Mpc}},$$

where $d_L(z)$ is the luminosity distance given by

$$d_L = (1 + z) \int_0^z \frac{dz'}{H(z')}.$$ 

We apply the Union data set of 307 SNIa [22], and place limits on the parameters $\alpha$, $\gamma$ and $\Omega_{\Lambda 0}$ by minimizing [23]

$$\chi^2_{\text{SN}} = A - \frac{B^2}{C},$$

where

$$A = \sum_{i=1}^{307} \left( \frac{\mu(z_i) - \mu_{\text{obs}}(z_i)}{\sigma_{\mu_i}} \right)^2,$$

$$B = \sum_{i=1}^{307} \frac{\mu(z_i) - \mu_{\text{obs}}(z_i)}{\sigma_{\mu_i}^2},$$

$$C = \sum_{i=1}^{307} \frac{1}{\sigma_{\mu_i}^2}.$$ 

Here, $z_i$ and $\mu_{\text{obs}}(z_i)$ are the redshift and the distance modulus of the $i$-th supernova, respectively. The corresponding 1σ error is denoted by $\sigma_{\mu_i}$.

The CMB shift parameter is one of the least model dependent parameters extracted from the CMB data. Since this parameter involves the large redshift behavior ($z \sim 1000$), it gives a complementary bound to the SNIa data ($z \lesssim 2$). The shift parameter $R$ is defined as

$$R = \sqrt{\Omega_{m0}} \int_0^{z_{\text{CMB}}} \frac{H_0}{H(z)} dz,$$

where $z_{\text{CMB}} = 1090$ is the redshift at recombination, and $\Omega_{m0} = \rho_{m0}/\rho_c0$ is the matter fraction at present. We use the value $R = 1.710 \pm 0.019$ obtained from the WMAP5 data [24]. The CMB constraints are given by minimizing

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

where $R_{\text{obs}} = 1.710$ and $\sigma_R = 0.019$. 

Observations of large-scale galaxy clustering provide the signatures of the baryon acoustic oscillation (BAO). We use the measurement of the BAO peak in the distribution of luminous red galaxies (LRGs) observed in SDSS [3]. It gives

\[ A = 0.469 \left( \frac{0.95}{0.98} \right)^{-0.35} \pm 0.017, \]  

where the parameter \( A \) is given by

\[ A = \sqrt{\Omega_{m0}} \left( \frac{H_0}{H(z_{BAO})} \right)^{1/3} \left[ \frac{1}{z_{BAO}} \int_0^{z_{BAO}} \frac{H(z)}{H_0} \, dz \right]^{2/3}, \]

and \( z_{BAO} = 0.35 \). The \( \chi^2 \) for BAO is

\[ \chi^2_{BAO} = \left( \frac{A - A_{\text{obs}}}{\sigma_A} \right)^2, \]

where \( A_{\text{obs}} = 0.469(0.95/0.98)^{-0.35} \) and \( \sigma_A = 0.017 \).

In Fig. 1, we plot the probability contours for SNIa (red), CMB (blue), BAO (green) observations in the \((\alpha, \Omega_{\Lambda0})\)-plane in the case without interaction \((\gamma = 0)\). The 1σ, 2σ and 3σ contours are drawn with solid, dashed and dotted lines, respectively. The joined constraints using \( \chi^2 = \chi^2_{\text{SN}} + \chi^2_{\text{CMB}} + \chi^2_{\text{BAO}} \) are shown as shaded contours. The best fit values with 1σ error are \( \alpha = 0.36 \pm 0.03 \) and \( \Omega_{\Lambda0} = 0.68 \pm 0.03 \) with \( \chi^2_{\text{min}} = 326 \). The joint 1σ region is outside the 1σ regions of CMB and BAO.

The same contour plots as Fig. 1 in the presence of interaction with \( \gamma = 0.15 \) are shown in Fig. 2. Compared to Fig. 1, the CMB contours are shifted to the right. The best fit values are shifted as \( \alpha = 0.45 \) and \( \Omega_{\Lambda0} = 0.73 \). It is remarkable to note that, unlike the case \( \gamma = 0 \), the joined 1σ region is included in all the 1σ regions of SNIa, CMB and BAO.

Dependence on the interaction parameter \( \gamma \) is presented in the \((\gamma, \alpha)\)-plane for \( \Omega_{\Lambda0} = 0.73 \) in Fig. 3. The best fit values are \( \gamma = 0.15 \pm 0.03 \) and \( \alpha = 0.45 \pm 0.03 \) with \( \sigma_+ = 0.25 \), \( \sigma_- = -3.0 \) and \( \chi^2_{\text{min}} = 313 \). It is found that the CMB constraint strongly depends on \( \gamma \). As a result, the joined 1σ region appears in the range with sizable \( \gamma \). This implies that existence of interaction between dark energy and matter is favored by cosmological constraints in the IRDE model.

### 4 Conclusions

We have considered the IRDE model where the interaction rate is given by eq. (8). We have derived the analytic expressions for the Hubble parameter (10) and the energy density of dark energy (15) and matter (16). Both \( \rho_\Lambda \) and \( \rho_m \) include contributions with non-standard time evolution. We have also investigated current observational constraints on this model from SNIa, CMB and BAO observations. In particular, the CMB constraint is strongly affected by the interaction. We have shown that a nonvanishing interaction rate is favored by the observations, giving a reduction of \( \chi^2_{\text{min}} \). The best fit values are \( \Omega_{\Lambda0} = 0.73 \pm 0.03 \), \( \alpha = 0.45 \pm 0.03 \) and \( \gamma = 0.15 \pm 0.03 \).
Figure 1: The probability contours for SNIa (red), CMB (blue), BAO (green) observations in the $(\alpha, \Omega_{\Lambda 0})$-plane in the case without interactions ($\gamma = 0$). The 1σ, 2σ and 3σ contours are drawn with solid, dashed and dotted lines, respectively. The joined constraints using $\chi^2 = \chi^2_{\text{SN}} + \chi^2_{\text{CMB}} + \chi^2_{\text{BAO}}$ are shown as shaded contours. The flat Universe ($k = 0$) is assumed in all the figures.
Figure 2: The same contour plots as Fig. 1 in the presence of interaction with $\gamma = 0.15$.

Figure 3: The contours of $\chi^2$ in the $(\gamma, \alpha)$-plane.
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