Probing the Coupling between Dark Components of the Universe (Postprint)

Authors: Zong-Kuan Guo, Nobuyoshi Ohta, Shinji Tsujikawa

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Abstract

We place observational constraints on a coupling between dark energy and dark matter by using 71 Type Ia supernovae (SNe Ia) from the first year of the five-year Supernova Legacy Survey (SNLS), the cosmic microwave background (CMB) shift parameter from the three-year Wilkinson Microwave Anisotropy Probe (WMAP), and the baryon acoustic oscillation (BAO) peak found in the Sloan Digital Sky Survey (SDSS). The interactions we study are (i) constant coupling #14; and (ii) varying coupling #14;(z) that depends on a redshift z, both of which have simple parametrizations of the Hubble parameter to confront with observational data. We find that the combination of the three databases marginalized over a present dark energy density gives stringent constraints on the coupling,$-0.08 <$ #14; < 0.03 (95% CL) in the constant coupling model and $-0.4 <$ #14;0 < 0.1 (95% CL) in the varying coupling model, where #14;0 is a present value. The uncoupled #3;CDM model (wX $= -1$ and #14; $= 0$) still remains a good fit to the data, but the negative coupling (#14; < 0) with the equation of state of dark energy wX < -1 is slightly favoured over the #3;CDM model.

Full Text

Preamble

Probing the Coupling between Dark Components of the Universe

Zong-Kuan Guo,[1] Nobuyoshi Ohta,[2] and Shinji Tsujikawa[3]
[1] Department of Physics, Kinki University, Higashi-Osaka, Osaka 577-8502, Japan
[2] Department of Physics, Kinki University, Higashi-Osaka, Osaka 577-8502, Japan
[3] Department of Physics, Gunma National College of Technology, Gunma 371-8530, Japan

[1] e-mail address: guozk@phys.kindai.ac.jp
[2] e-mail address: ohtan@phys.kindai.ac.jp
[3] e-mail address: shinji@nat.gunma-ct.ac.jp

Abstract

We place observational constraints on a coupling between dark energy and dark matter using 71 Type Ia supernovae (SNe Ia) from the first year of the five-year Supernova Legacy Survey (SNLS), the cosmic microwave background (CMB) shift parameter from the three-year Wilkinson Microwave Anisotropy Probe (WMAP), and the baryon acoustic oscillation (BAO) peak found in the Sloan Digital Sky Survey (SDSS). The interactions we study are (i) constant coupling and (ii) varying coupling (z) that depends on redshift z, both of which have simple parametrizations of the Hubble parameter to confront with observational data. We find that the combination of the three datasets marginalized over the present dark energy density gives stringent constraints on the coupling: $-0.08 < \ < 0.03$ (95% CL) in the constant coupling model and $-0.4 < \ < 0.1$ (95% CL) in the varying coupling model, where is the present value. The uncoupled ΛCDM model (w $= -1$ and $= 0$) still remains a good fit to the data, but negative coupling (< 0) with the equation of state of dark energy w < -1 is slightly favored over the ΛCDM model.

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Introduction

Recent observations of Supernova Ia (SNIa) suggest that the universe has entered a stage of accelerated expansion with redshift z 1 [?, ?, ?]. This has been confirmed by precise measurements of the spectrum of Cosmic Microwave Background (CMB) anisotropies [?, ?] as well as baryon acoustic oscillations (BAO) in the Sloan Digital Sky Survey (SDSS) luminous galaxy sample [?]. As is well known, all usual types of matter with positive pressure generate attractive forces that decelerate the expansion of the universe. Given this, a dark energy component with negative pressure was suggested to account for the invisible fuel that drives the current accelerated expansion (see Refs. [?, ?] for reviews).

The simplest candidate for dark energy is a cosmological constant Λ (vacuum energy), which corresponds to a constant equation of state w $= -1$. This model, the so-called ΛCDM, provides an excellent fit to a wide range of astronomical data so far. However, such a model suffers from a theoretical problem of cosmic coincidence: why is the vacuum density comparable with the critical density at the present epoch in the long history of the universe?

One possible approach to alleviating this problem is to assume that the "cosmological constant" is not constant but is instead a dynamical component with a slowly evolving, spatially homogeneous scalar field called quintessence [?] (see

Refs. [?] for early works and Refs. [?] for the reconstruction of quintessence potentials). In such models, the resolution of the cosmic coincidence problem typically leads to fine-tuning of model parameters.

Given that the amount of dark matter is comparable to that of dark energy in the present universe, it is natural to consider an interaction between the two components. Originally, cosmological consequences of a scalar field coupled to matter were studied in Ref. [?]. Amendola [?] considered interaction between a quintessence field and dark matter with a coupling Q that satisfies the relation T^{ }_{ ( ); } = QT^{(m)} ; between energy-momentum tensors. In fact, this type of interaction appears in the context of scalar-tensor theories [?], f(R) gravity models [?], varying mass dark matter/neutrino models [?, ?, ?, ?], and phantom dark energy models [?]. Interestingly, the equation of state of dark energy can extend to the region w < -1 if the mass of dark matter depends on a quintessence field [?, ?]. The presence of the coupling can also provide an accelerated scaling attractor along which the ratio of the energy densities of dark energy and dark matter is constant. This may be useful for solving the coincidence problem because the present universe can be a global attractor with a dark energy fraction Ω 0.7.

However, the coupling Q required to realize the accelerated scaling attractor is too large to ensure the presence of a standard matter-dominated epoch [?]. In fact, there exists the so-called " matter-dominated epoch" (MDE) during which an effective equation of state is given by w_eff = $2Q^2/3$ [?, ?, ?]. Amendola [?] showed that the coupled quintessence model with an exponential potential is not consistent with observational CMB data unless the coupling Q is smaller than order 0.1, but in this case there is no scaling accelerated attractor. Instead, the system finally approaches a scalar-field-dominated attractor with w_eff = -1 and Ω = 1, in which case the coincidence problem is not solved.

There are many other scalar-field dark energy models such as K-essence, tachyon, phantom, and dilatonic ghost condensates. For a general Lagrangian density p(, X) with a kinetic term X = $-(1/2)(\ )^2$ and a constant coupling Q, the existence of scaling solutions required to solve the coincidence problem restricts the Lagrangian density to the form p = Xg(Xe^{ }), where g is an arbitrary function and is a constant [?]. Recently it has been shown that for the vast class of this generalized Lagrangian that includes most scalar-field dark energy models, the matter era is not followed by the accelerated scaling attractor [?]. Thus, it remains a challenging task to construct coupled scalar-field models that can solve the coincidence problem without using fine-tuned varying couplings [?].

Since the origin of dark energy is not yet known, there are several different approaches [?, ?, ?, ?, ?] to implementing couplings without restricting to scalar-field models (see also Refs. [?]-[?] for a number of interesting aspects of interacting dark energy). The approach we adopt in this paper is to introduce an interaction of the form Γ on the right-hand side of conservation equations, see (2) and (3). While this is basically a fluid description of dark energy, Eqs.

(2) and (3) include the aforementioned scalar-field coupling by setting $\Gamma = Q\dot{}$. Since the interaction rate Γ measured by the Hubble rate H is generally important for discussing the strength of energy transfer, we introduce a dimensionless coupling in the form $= \Gamma/H$. This is an approach a number of authors have adopted [?]. One can constrain the strength of the interaction observationally by assuming that is constant (as in the constant Q case discussed above). In fact, the authors in Ref. [?] recently placed observational constraints on the coupling using SNIa data with a parametrization of the dark energy equation of state $w = w + w z$.

It is also possible to address the varying case. For example, Dalal et al. [?] assumed that the ratio of dark energy and dark matter has a relation / $a\hat{}$, where a is the scale factor and is a constant. For a constant equation of state of dark energy, the coupling is known as a function of redshift z [?], see Eq. (12). Since the strength of the coupling decreases for larger z, this scenario can address the situation in which the interaction is weak during the matter era but becomes strong in the dark energy-dominated epoch.

Observational constraints on the coupling $= \Gamma/H$ have been obtained using SNIa data [?, ?]. In this paper, we carry out likelihood analysis of coupled dark energy models using 71 high-redshift SNe Ia from the first year of the five-year SNLS, the CMB shift parameter from the three-year WMAP observations, and the BAO peak found in the SDSS. We concentrate on two classes of interacting models: (i) a constant coupling and (ii) a varying coupling (z) with the relation / $a\hat{}$. Throughout this paper, the dark energy equation of state w is assumed to be constant.

In both models, we have three free parameters (, w , Ω), where Ω is the present energy fraction of dark energy (in the varying coupling model is replaced by the present value). We find that the combination of the three datasets places stringent constraints on the model parameters since the CMB shift parameter is sensitive to the value of the coupling. Our results also indicate that the concordance ΛCDM model still remains a good fit to the data, but negative coupling (< 0) with the equation of state of dark energy $w < -1$ is slightly favored over the ΛCDM model.

Interactions Between Dark Energy and Dark Matter

In this section, we explain the form of the interaction between dark energy and dark matter. The background metric is described by the flat Friedmann-Robertson-Walker (FRW) metric with a scale factor a: $ds^2 = -dt^2 + a^2(t)dx^2$, where t is cosmic time. Quite generally we can write the conservation equations in the forms

$$\dot{} + 3H = +\Gamma , (2)$$
$$\dot{} + 3H(+ p) = -\Gamma , (3)$$

where $H = \dot{a}/a$ is the Hubble rate, and are the energy densities of dark matter and dark energy respectively, and p is the dark energy pressure density with the equation of state w = p / . If we consider a scalar-field model of dark energy, the interaction term is typically given by Γ = Q˙, where the constant Q characterizes the strength of the coupling [?, ?]. Amendola obtained the constraint on the coupling as Q < 0.08 using information from the CMB power spectrum.

We note that the origin of dark energy is not yet identified as a scalar field. In this work we take a different approach to constraining the strength of the interaction without assuming scalar-field models. We measure Γ in terms of the Hubble parameter H and define the dimensionless coupling = Γ/H.

Note that a positive implies a transfer of energy from dark energy to dark matter, and vice versa. From Eqs. (2) and (3) it is clear that the total energy density is conserved. Neglecting the contributions of (uncoupled) baryon and radiation components, the Friedmann equation is given by

$3H^2 = {}^2(+),$ (5)

where $^2 = 8$ G with G being the gravitational constant.

In the following, we first discuss the case in which is constant. Then the analysis is extended to the case in which varies in time and the ratio of the energy densities of dark energy and dark matter scales as / a^ .

A. Constant Coupling Models

For constant [?, ?], Eq. (2) is easily integrated to

$= a^{3} = (1 + z)^3$, (6)

where the subscript "0" represents present values. Note that z is the redshift defined by z = a /a − 1, where a is normalized as a = 1. Equation (6) shows that the interaction leads to a deviation from the usual conservation relation a ³.

We assume that w is constant. Then substituting Eq. (6) into Eq. (3), we obtain the integrated solution

$= (1 + z)^{3\ 1} + ( )/(+ 3w)[(1 + z)^{3\ 1} - (1 + z)^3].$ (7)

Using the Friedmann equation (5), we find

$E^2(z) = \Omega\ (1 + z)^{3\ 1} + (1 - \Omega\ )(/(+ 3w))(1 + z)^{3\ 1} - (/(+ 3w))(1 - \Omega\ )(1 + z)^3$, (8)

where E(z) = H(z)/H and Ω = ² /(3H ²). Thus we have three free parameters (, w , Ω) when we confront models with observations. This allows us to parameterize a wide range of possible cosmologies in a simple fashion.

In the high redshift region (z 1), it follows from Eq. (7) that behaves as

$- /(+ 3w)(1 + z)^3$ for 3w < − .

This means that the energy density of dark energy becomes negative for < 0. Since such negative energy appears in phantom models [?] and also modified gravity models [?, ?], we do not exclude the possibility of negative coupling. Note also that in the high redshift region we have the scaling relation $/ = - /(+ 3w)$. If $| |$ is much smaller than 1, the ratio satisfies $| / |$ 1 provided that w is of order -1.

With the parametrization given above, we can classify the models into four types in the (w ,) plane: (i) decaying phantom characterized by > 0 and w < -1, (ii) decaying quintessence characterized by > 0 and w > -1, (iii) created quintessence characterized by < 0 and w > -1, and (iv) created phantom characterized by < 0 and w < -1, as shown in Fig. 1.

Here we use the word "quintessence" for dark energy satisfying w > -1 without restricting to scalar-field models.

In this plane, the horizontal dashed line represents the uncoupled models with $= 0$ and the vertical dashed line represents the coupled ΛCDM models with w $= -1$.

B. Varying Coupling Models

When varies in time, Eq. (2) together with Eq. (4) gives

= a ³e^{ d(ln a)}. (9)

Let us now consider a situation in which the ratio of dark energy and dark matter has the following relation [?]:

/ a^ , (10)

where is a constant that quantifies the severity of the coincidence problem. In the absence of coupling with constant w , the energy density of dark energy scales as a ³ ¹ . Here the ratio / is proportional to a ³ , namely, the $= -3w$ case in Eq. (10). Note that the standard ΛCDM model corresponds to w $= -1$ and $= 3$.

The general case $-3w$ indicates the existence of an interaction between dark matter and dark energy. Using relation (10), we find that the coupling Γ is given by $\Gamma = -H(+ 3w)\Omega (z)$, where $\Omega (z) = {}^2 /(3H^2)$. This shows that varies according to the change of Ω as

(z) = −(+ 3w)Ω (z). (11)

When $= -3w$, this reduces to $= 0$. Since Ω (z) is given by

Ω (z) = Ω (1 + z)^ / [Ω + (1 − Ω)(1 + z)^]

under condition (10), the coupling can be written as

(z) = (1 + z)^ / [Ω + (1 − Ω)(1 + z)^], (12)

where $= -(+ 3w)\Omega$. If > 0, (z) decreases for higher z.

Note that the = 0 case gives a constant coupling (z) = . Since this corresponds to an exact scaling solution , one cannot realize the matter-dominated epoch followed by late-time acceleration. This constant case is different from the one we discussed in subsection A. In fact, the solutions (6) and (7) do not satisfy relation (10).

From Eqs. (2) and (3) together with Eq. (10), the total energy density _T = + satisfies

d ln _T/d ln a = −3[1 + w Ω (z)], (13)

which can be integrated to give

_T = _T a ³[Ω + (1 − Ω)a^] ³ / . (14)

Then the Friedmann equation (5) gives

$E^2(z) = (1 + z)^3$[Ω + (1 − Ω)(1 + z)^] ³ / . (15)

From Eq. (10), we find that the energy density of dark energy is given by

= _T Ω / [Ω + (1 − Ω)(1 + z)^]. (16)

We have three parameters (, w , Ω) in this model. Since is related to these variables by = −(+ 3w)Ω , one can instead vary three parameters (, w , Ω) when carrying out likelihood analysis. Thus model (15) is a simple parametrization that implements the variation of the coupling . Note that both _T and are positive as long as 0 < Ω < 1. Hence remains positive in the high-redshift region even for < 0, unlike the constant coupling model.

The coupling affects the evolution of quantities of interest, such as the age of the universe and the deceleration parameter. Given w and Ω , the age of the universe and the transition redshift at which the universe switches from deceleration to acceleration become larger as the value of increases from negative to positive. In the next section, we place observational constraints on the strength of the coupling.

III. Constraints from Recent Observations

In this section, we study the viability of interacting models presented in the previous section using recently released SNLS data [?] in conjunction with the BAO peak in the SDSS [?] and the CMB shift parameter [?].

Recently, Astier et al. [?] compiled a new sample of 71 high-redshift SNe Ia in the redshift range 0.2 < z < 1.0, discovered during the first year of the 5-year SNLS. This dataset is arguably the best high-redshift SN Ia compilation, as it adopts multi-band, rolling search techniques and careful calibration. The luminosity distance d_L(z) to supernovae is given by [?, ?]

d_L(z) = (c/H)(1 + z) ^z dz /E(z). (17)

The baryon oscillations in the galaxy power spectrum are imprints from acoustic oscillations prior to recombination, which are also responsible for the acoustic peaks seen in the CMB temperature power spectrum. The physical length scale associated with the oscillations is set by the sound horizon at recombination, which can be estimated from CMB data [?]. Measuring the apparent size of the oscillations in a galaxy survey allows one to measure the angular diameter distance at the survey redshift. Although the acoustic features in the matter correlations are weak on large scales, Eisenstein et al. [?] successfully found the peaks using a large spectroscopic sample of luminous red galaxies from SDSS [?]. This sample contains 46,748 galaxies covering 3816 square degrees out to a redshift of z = 0.47. They found a parameter A that is independent of dark energy models [?]. From Eq. (5) in their paper [?], we write it as

A = √Ω   [E(z)] ¹ ³ [(1/z)   ^{z } dz /E(z)]² ³, (18)

where z = 0.35 and A is measured to be A = 0.469 ± 0.017. In our analysis, we combine these measurements.

The CMB shift parameter R captures the correspondence between the angular diameter distance to the last scattering surface and the relation of the angular scale of the acoustic peaks to the physical scale of the sound horizon [?]. Its value is expected to be mostly model-independent and can be extracted accurately from CMB data. The shift parameter R is given by [?]

R = √Ω   ^{z_rec} dz /E(z), (19)

where z_rec is the redshift of recombination. It provides a useful constraint on evolving dark energy models since the integral over E(z) extends to high redshifts. The recent analysis of three-year WMAP data [?] gives R = 1.70 ± 0.03 at z_rec = 1089 [?].

A. Constant Coupling Models

Let us first consider observational constraints on constant coupling models. In Fig. 1, we show probability contours from SNLS when we take a prior for Ω such that the probability distribution is Gaussian with mean 0.72 and standard deviation   = 0.04. We also assume the condition   < 3 to exclude the possibility that dark matter behaves as phantom matter [see Eq. (6)], which would be problematic for successful structure formation. Then we find that the SNLS data gives a weak constraint on the coupling: −1.78 <   < 3 at the 95% confidence level. When we choose a wider range for the prior on Ω , the constraint becomes weaker.

Figure 2 shows the case in which BAO data is taken into account in addition to SNLS data without a prior for Ω . Compared to Fig. 1, the allowed range of w is reduced. However, we still have a rather large region of parameter space for , i.e., −1.73 <   < 3 (95% CL).

We have also carried out likelihood analysis without any prior for   and found that even large couplings such as $= 20$ with w -0.7 are within the 2 observational contour bound. This reflects the fact that SNIa and BAO data give constraints only around low redshifts $z < O(1)$. The models can fit the data even for 1 because of the dominance of the $(1 + z)^{3\ 1}$ term instead of the usual 3w $(1 + z)^3$ term on the right-hand side of Eq. (8). This demonstrates how important it is to include other data in the high-redshift region (z 1) in order to rule out models with problematic couplings (> 3). In fact, the CMB shift parameter provides a stringent constraint on the coupling.

In Fig. 3 we plot observational contours from the joint analysis of SNLS, CMB, and BAO data in the (w ,) plane marginalized over Ω (left panel) and in the (Ω ,) plane marginalized over w (right panel). Note that we do not put any prior on in these analyses. We find that the coupling is severely constrained: $-0.08 <$ < 0.03 (95% CL) in both marginalizations. This comes from the fact that CMB data do not allow large deviations from the standard matter-dominated epoch.

The combined analysis of three datasets constrains the equation of state and present energy fraction of dark energy to $-1.16 <$ w < -0.91 and $0.69 <$ Ω $<$ 0.77 (95% CL). It is interesting to note that the allowed observational contours are widely spread in the phantom region (w < -1) with negative coupling ($<$ 0), see Fig. 3. The best-fit parameters are found to be $= -0.03$, w $= -1.02$, and Ω $= 0.73$ with $^2 = 60.94$, which is slightly favored over the ΛCDM model.

B. Varying Coupling Models

We now proceed to varying coupling models in which depends upon z in the form (12). In Fig. 4 we show observational contours from the combined analysis of SNLS+BAO+CMB data in the planes (i) (w ,) marginalized over Ω (left panel) and (ii) (Ω ,) marginalized over w (right panel). We find that the present coupling, dark energy equation of state, and present dark energy density are constrained to be $-0.4 <$ < 0.1, $-1.18 <$ w < -0.91, and $0.69 <$ Ω < 0.77 at the 95% confidence level. The best-fit parameters correspond to $= -0.11$, w $= -1.03$, and Ω $= 0.73$ with $^2 = 60.94$. Similar to the constant coupling case, SNIa and BAO data do not provide stringent constraints on , but inclusion of CMB data significantly reduces the allowed region of the coupling. Since (z) decreases for larger z, the observational constraints on are not as severe compared to the constant coupling models. We also find that phantom models (w < -1) with negative coupling (< 0) have a wider allowed parameter space compared to the other three divided regions in the left panel of Fig. 4.

As we see from Fig. 5, the ΛCDM model, which corresponds to the point (w ,) $= (-1, 3)$, is within the 1 contour bound. We remind that uncoupled models are characterized by the line $= -3$w . Thus, provided that points are not on the line $= -3$w , the coupled models are allowed observationally in the parameter regions $2.66 <$ < 4.05 (95% CL). From Fig. 5 it is obvious that scaling models with $= 0$ are excluded by the data.

IV. Conclusions

In this paper, we have studied interacting models of dark energy in which the coupling between dark matter and dark energy is given by (4) together with conservation equations (2) and (3). We discussed two different models: (i) the constant case, and (ii) the varying case which has redshift dependence given in (12). The latter type of coupling appears by imposing the relation / a^ between the energy densities of the two dark components. Assuming that the equation of state of dark energy w is constant, we obtained convenient forms of the Friedmann equations (8) and (15) to confront with observational data.

We have placed observational constraints on the strength of the coupling using recent SNLS data, the CMB shift parameter, and SDSS baryon acoustic oscillations (BAO). In both constant and varying coupling models, supernova data alone do not provide stringent constraints on the coupling. Adding BAO data generally reduces the allowed range of w , but coupling of order unity is still not ruled out. This reflects the fact that BAO and SN Ia data are sensitive to the value of w or Ω rather than . However, the combined analysis of SNLS+BAO+CMB shows that the allowed region of the coupling is significantly reduced compared to the case without CMB data. This is associated with the fact that a large coupling leads to changes in cosmological evolution during the matter-dominated epoch, thus modifying the CMB angular-diameter distance.

By the joint analysis of SNLS+BAO+CMB, we have obtained observational constraints on the strength of the coupling: (i) $-0.08 < \; < 0.03$ (95% CL) for constant coupling models and (ii) $-0.4 < \; < 0.1$ (95% CL) for varying coupling models (where is the present value). We also find that best-fit values exist in the phantom region ($w < -1$) with negative coupling (< 0) in both constant and varying coupling models. The uncoupled ΛCDM model ($w = -1$ and $= 0$) still remains a good fit to the data. Nevertheless, it is interesting to note that negative coupling with dark energy having $w < -1$ is slightly favored over the ΛCDM model.

There exist coupled dark energy models [?, ?] that give $w < -1$ without using a negative kinetic energy of a scalar field (called "super-acceleration" in Ref. [?]). This can be realized by considering scalar-field dependent masses of dark matter particles. It was shown in Ref. [?] that this super-acceleration model satisfies a number of observational constraints, which is consistent with our results that the equation of state $w < -1$ is favored.

In this work we did not take into account observational constraints from matter density perturbations , which are also affected by the presence of the coupling [?]. It was shown in Ref. [?] that inclusion of matter density perturbations can place stronger constraints on the coupling compared to analysis using background evolution only. Future galaxy surveys such as KAOS and PANSTARRS will provide high-accuracy data of the matter power spectrum, which may offer the possibility to put severe constraints on the coupling. This may provide an exciting opportunity to reveal the origin of dark energy and dark matter.

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