Probing inflation and dark energy with current cosmological observations

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Abstract. It is commonly believed that our Universe has experienced at least two different stages of accelerated expansion. The early stage is known as inflation and the current acceleration is driven by dark energy. Observing inflation and dark energy dynamics are among the most important aspects of current cosmological research. In this paper we carry out a first detailed probe of the possible degeneracies between dynamical inflation and dark energy in the light of the current cosmological observations. We have combined type Ia supernova (Riess ‘gold’ samples), galaxy clustering (SDSS 3D power spectra) and the Wilkinson Microwave Anisotropy Probe (WMAP) observations and performed a global analysis using the Markov chain Monte Carlo method. We find the inclusion of inflation and dark energy parameters together makes the parameter spaces broader and the degeneracies among the inflation dark energy parameters are non-trivial: the allowed/preferred behaviour of dynamics in one sector is dependent on the prior of the other sector. Interestingly a deviation from a scale invariant primordial spectrum is slightly preferred by the current cosmological observations when one marginalizes over dynamical dark energy models.

Keywords: dark energy theory, inflation

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1. Introduction

Recent advances in both theoretical and observational cosmology have revealed that our Universe has experienced two different stages of accelerated expansion. One is the inflation in the very early universe when its tiny patch was superluminally stretched to become our observable Universe today [1, 2]. This can naturally explain why the universe is flat, homogeneous and isotropic. Inflation is driven by a potential energy of a scalar field called inflaton and its quantum fluctuations turn out to be the primordial density fluctuations which seed the observed large-scale structures (LSS) and anisotropy of cosmic microwave background radiation (CMB). In the past decade, inflation theory has successfully passed several non-trivial tests. In particular, the released first-year Wilkinson Microwave Anisotropy Probe (WMAP) data [3] have detected a large-angle anticorrelation in the temperature–polarization cross-power spectrum, which is the signature of adiabatic superhorizon fluctuations at the time of decoupling [4]. The cosmological observations such as the first-year WMAP (WMAP1) and the Sloan Digital Sky Survey (SDSS) ones are in good agreement with an adiabatic and scale invariant primordial spectrum (see e.g. [5, 6]), which is consistent with single-field slow rolling inflation predictions. On the other hand, however, inflation generically predicts a primordial spectrum with some deviations from scale invariance and it is crucial to probe the scale dependence of the primordial spectrum in the light of the cosmological observations. The tentatively interesting features of the first-year WMAP observations have aroused a lot of interest as regards explaining such effects with the dynamics of inflation [7].

In 1998 the analysis of the redshift–distance relation of type Ia supernova (SNIa) revealed the existence of the second stage of accelerated expansion that started rather recently when a mysterious new energy component dubbed dark energy (DE) dominated the energy density of the Universe [8, 9]. Recent observations of SNIa have confirmed the accelerated expansion at high confidence level [10]–[13]. The nature of dark energy is among the biggest problems in modern physics and has been studied widely. A cosmological constant, the simplest DE candidate where the equation of state (EOS) \( w \) remains \(-1\), suffers from the well-known fine-tuning and coincidence problems. Alternatively, dynamical dark energy models with rolling scalar fields have been proposed, such as quintessence [14, 15], phantoms [16] and \( k \)-essence [17, 18]. Given that currently...
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we know very little of the theoretical aspects of dark energy, the cosmological observations play a crucial role in our understanding of dark energy. If the observations strongly favour a dark energy component with a deviation from \( w = -1 \), then the cosmological constant which puzzles the theorists would not be the source driving current acceleration of the universe.

Since there are many common aspects of the background physics, albeit the striking difference of the energy scale between the two stages of accelerated expansion, it would be nice if one could unify inflation with dark energy. The model of quintessential inflation \[19\] has been proposed historically trying to unify the two epochs of accelerated expansions. The first-year WMAP observations show a lack of a temperature–temperature correlation power on the largest scales and many studies have attributed this to the suppressed primordial spectrum due to some dynamics of the inflaton. Intriguingly, in \[20\] the authors attributed the lack of power to the isocurvature fluctuations in the quintessence which may be generated during inflation, and thus the different dynamics of the dark energy sector and inflation can lead to similar effects on the observations, where such a degeneracy may reflect the possible connections between dark energy and inflation.

Observing inflation and dark energy dynamics are among the most important aspects of the current cosmological research. So far to our knowledge in the previous observational studies of dynamical dark energy or inflation not enough attention has been paid to the possible correlation between the two sectors: dark energy and inflation. In this paper we carry out a first detailed probe of the possible degeneracies between dynamical inflation and dark energy in the light of the current cosmological observations. Our paper is structured as follows: in section 2 we describe the method and the data; in section 3 we present our results through global fittings; finally we give our summary and conclusions in section 4.

2. Method and data

The role of the primordial scalar spectral index \( n_s \) in the probing of inflation is somewhat similar to that of the dark equation of state \( w \) in the measurement of dark energy. The case of \( n_s = 1 \) corresponds to the scale invariant Harrison–Zel’dovich spectrum, where the scalar spectrum is constant over all scales and \( w = -1 \) corresponds to the cosmological constant where the density of dark energy does not evolve with time. A detection of deviation from \( n_s = 1 \) or \( w = -1 \) would mark a breakthrough in our understanding of inflation and dark energy. To make our study on inflation and dark energy symmetric and in some sense model independent, we parametrize \( n_s \) and \( w \) with linear expansions and keep them to first order:

\[
n_s(k) = n_s(k_{s0}) + \alpha_s \ln \left( \frac{k}{k_{s0}} \right),
\]

(1)

where \( k_{s0} \) is a pivot scale which is arbitrary in principle and \( \alpha_s \) is a constant characterizing the ‘running’ of the scalar spectral index. The scalar spectral index \( n_s \) is related to the primordial scalar power spectrum \( P_\chi(k) \) by definition:

\[
n_s(k) \equiv dP_\chi(k)/d\ln k + 1.
\]

(2)
Correspondingly $P_X(k)$ is now parametrized as [21]

$$\ln P_X(k) = \ln A_s + (n_s(k_{s0}) - 1) \ln \left( \frac{k}{k_{s0}} \right) + \frac{a_s}{2} \left( \ln \left( \frac{k}{k_{s0}} \right) \right)^2.$$  (3)

Accordingly for the dark energy sector the equation of state is parametrized as [22]

$$w_{DE}(a) = w_0 + w_1 (1 - a)$$  (4)

where $a = 1/(1 + z)$ is the scale factor and $w_1$ characterizes the ‘running’ of the equation of state. The equation of state is defined as the pressure over the energy density, which leads to the evolution of dark energy density via the energy conservation of dark energy:

$$\frac{\rho_Q(a)}{\rho_Q(a_0 = 1)} = a^{-3(1 + w_0 + w_1)} \exp[3w_1(a - 1)].$$  (5)

The currently publicly available codes like CMBfast [23, 24] and CAMB [25, 26] have adapted well the constant running of the primordial spectral index. For the constant running of the dark energy equation of state the situation is not so straightforward [27, 28].

For the common dynamical dark energy models like quintessence and phantoms, the equation of state does not get across $-1$, and for the global fittings through parametrizations of $w$ the dynamics of quintessence or phantoms has been fully enclosed in $w$ in which sense one can even reconstruct the potentials of quintessence and phantoms with $w$. However in the cases where $w$ gets across $-1$ during evolution, single-field scalar dark energy models like quintessence, phantoms and $k$-essence cannot realize such a transition and, on the other hand, for the parametrized dark energy one encounters the problem of divergence for the perturbation equations [28]. These properties have been investigated in detail in our companion paper in [28]. Dark energy with an equation of state getting across $-1$ has been dubbed ‘quintom’ in the sense that it resembles the combined behaviour of quintessence and a phantom [29]–[31]. We have shown that in general to realize the quintom model one needs to add extra degrees of freedom beyond the standard single-field case [28]. In the extant two-field-quintom model and the single-field model with a high derivative term [32], the perturbation of dark energy is shown to be continuous when $w$ gets across $-1$.

For the parametrization of the equation of state which gets across $-1$, we introduce a small positive constant $\epsilon$ to divide the full range of the allowed value of $w$ into three parts: (1) $w > -1 + \epsilon$; (2) $-1 + \epsilon \geq w \geq -1 - \epsilon$; and (3) $w < -1 - \epsilon$. Working in the conformal Newtonian gauge, one can easily describe the perturbations of dark energy as follows [33]:

$$\dot{\delta} = -(1 + w)\left(\theta - 3\dot{\Phi}\right) - 3\mathcal{H}(c_s^2 - w)\delta,$$  (6)

$$\dot{\theta} = -\mathcal{H}(1 - 3w)\theta - \frac{w}{1 + w}\theta + k^2 \left( \frac{c_s^2\delta}{1 + w} + \Psi \right).$$  (7)

Neglecting the entropy perturbation contributions, for the regions (1) and (3) the equation of state does not get across $-1$ and perturbations are well defined by solving equations (6) and (7). For case (2), the perturbation of energy density $\delta$ and divergence of velocity, $\theta$, and the derivatives of $\delta$ and $\theta$ are finite and continuous for the realistic quintom dark energy models. However for the perturbations of the parametrized quintom
there is clearly a divergence. In our study for such a regime, we match the perturbation in region (2) to those of the regions (1) and (3) at the boundary and set \[ \dot{\delta} = 0, \quad \dot{\theta} = 0. \] (8)

In our numerical calculations we have limited the range to \(|\Delta w = \epsilon| < 10^{-5}\) and we find that our method is a very good approximation to the multi-field quintom. For more details of this method we refer the readers to our previous companion paper [28].

In this study we have implemented the publicly available Markov chain Monte Carlo package CosmoMC [34], which has been modified to allow for the inclusion of dark energy perturbation with the equation of state getting across \(-1\). We assume purely adiabatic initial conditions and a flat Universe. Our most general parameter space is

\[
P = (\omega_b, \omega_c, \Theta_s, \tau, w_0, w_1, n_s, \alpha_s, \ln(10^{10} A_s), r)
\]

where \(\omega_b \equiv \Omega_b h^2\) and \(\omega_c \equiv \Omega_c h^2\) are the physical baryon and cold dark matter densities relative to the critical density, \(\Theta_s\) is the ratio (multiplied by 100) of the sound horizon to the angular diameter distance at decoupling, \(\tau\) is the optical depth to reionization, \(A_s, n_s\) and \(\alpha_s\) characterize the primordial scalar power spectrum. \(r\) is the tensor to scalar ratio of the primordial power spectrum and for the tensor slope \(n_T\) we have fixed \(r = -8n_T\). For the pivot of the primordial spectrum we set \(k_{s0} = 0.05\) Mpc\(^{-1}\). Furthermore, we make use of the Hubble Space Telescope (HST) measurement of the Hubble parameter \(H_0 \equiv 100h\) km s\(^{-1}\) Mpc\(^{-1}\) [35] by multiplying the likelihood by a Gaussian likelihood function centred around \(h = 0.72\) and with a standard deviation \(\sigma = 0.08\). We also impose a weak Gaussian prior on the baryon and density \(\Omega_b h^2 = 0.022 \pm 0.002\) (1\(\sigma\)) from big bang nucleosynthesis [36].

In our calculations we have taken the total likelihood to be the products of the separate likelihoods \(\mathcal{L}_i\) of CMB, LSS and SNIa. In other words defining \(\chi^2_i \equiv -2 \log \mathcal{L}_i\), we get

\[
\chi^2_{\text{total}} = \chi^2_{\text{CMB}} + \chi^2_{\text{LSS}} + \chi^2_{\text{SNIa}}.
\]

We have included the first-year temperature and polarization data with the routine for computing the likelihood supplied by the WMAP team [3, 37]. We use the code developed in [38] to fit the 3D power spectrum of galaxies from the SDSS and the bias factor of SDSS has been used as a continuous parameter to give the minimum \(\chi^2\) value. For the SNIa data we use the 157 gold sample data published by Riess et al [11] and in the calculation of the likelihood we have marginalized over the nuisance parameter [39].

Compared with Riess ‘gold’ sample of SNIa, the first-year Supernova Legacy Survey (SNLS) sample [13] has been measured with one telescope and the systematics are better constrained. However for the time being their determinations of cosmological parameters are marginally comparable [40]. Due to the fact that the two samples of SNIa have come from different methods of light curve fitting a combination of them is not so straightforward. For LSS for the time being the two-degree field (2dF) [41] and SDSS [38] are also comparable and for the current study we have not combined the two data sets simultaneously.

For each ordinary calculation, we run eight independent chains comprising 150,000–300,000 chain elements and spend thousands of CPU hours for calculation on a supercomputer. The average acceptance rate is about 40%. We test the convergence of the chains using the Gelman and Rubin criteria [42] and find that \(R - 1\) is of order 0.01 which is more conservative than the recommended value \(R - 1 < 0.1\).
3. Results

To get clear the effects on the possible correlations between dynamical inflation and dark energy we mainly focus on three kinds of models: one is the ΛCDM cosmology where \( n_s, r \) and \( \alpha_s \) are enclosed in the inflationary sectors; one is with a scale invariant primordial spectrum (\( r \) not included) where \( w_0 \) and \( w_1 \) are included in the dark energy sector; and the third one includes all of the free parameters like \( n_s, r, \alpha_s, w_0 \) and \( w_1 \).\(^3\)

Table 1 lists all of the relevant one-dimensional median values and 1σ constraints for the three models specified above. Shown together are the minimum \( \chi^2 \) values for each case. For the constraints on \( r \) only 2σ upper bounds have been shown. The effects of different priors on the inflationary and dark energy sectors will be explained in detail with the two-dimensional graphics of the subparameter space below.

In figure 1 we delineate the two-dimensional contours of the primordial spectrum parameters by marginalizing over ΛCDM cosmology (blue dashed lines) and over dynamical dark energy with the equation of state a equation (4) (red solid lines). The contours stand for 68% and 95% C.L. Although in general the case with dynamical dark energy gives less stringent constraints on the primordial spectrum, the ΛCDM case does not overlap fully with the dynamical dark energy case. Intriguingly for the combination with the inclusion of dark energy dynamics, the constraints on the tensor contributions exhibit different behaviours at 68% and 95% C.L. and at 68% C.L. The constraint on \( r \) is more stringent with the inclusion of dark energy dynamics, which is different from what is naively expected. This can be explained by the mild preference of the dark energy dynamics in the combination WMAP1 + SDSS + SNIa (Riess) and the degeneracy between dark energy dynamics and \( r \) on the largest scales of CMB. From table 1 we can find the preference for dynamical DE is slightly larger than 1σ from the different minimum \( \chi^2 \) values as well as from the one-dimensional constraint on the parameter of \( w_0 \). Also we can see some difference in the constraints on \( \alpha_s \) and the value of \( n_s \) at 0.05 Mpc\(^{-1}\). Note that the best fit values of \( \alpha_s \) in some sense deviate a lot from zero; the difference for the probe of the scale variance may be non-negligible for the two cases. We get \( \alpha_s = -0.032^{+0.046}_{-0.035} \) for the ΛCDM cosmology and \( -0.040^{+0.037}_{-0.036} \) instead for the case with dynamical dark energy. Roughly speaking a scale invariant primordial spectrum is not

\(^3\) For simplicity of discussion we do not discuss the effects on \( A_s \) and \( \Omega_{DE} \), although we did vary them in our fittings.

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Figure 1. Constraints on the primordial spectrum parameters from marginalizing over ΛCDM cosmology (blue dashed line) and over dynamical dark energy with equation of state $w = w_0 + w_1(1-a)$ (red solid line). The two-dimensional contours stand for 68% and 95% C.L.

yet ruled out in the ΛCDM cosmology while it is disfavoured more than 1σ when we allow the dynamics of dark energy! We will return to this in more detail in a later part of this paper.

In figure 2 we plot the 68% and 95% constraints on the $(w_0, w_1)$ contour marginalizing over the scale invariant primordial spectrum (blue dashed line) and over the primordial spectrum with a running spectral index (red solid line). We find it interestingly that the 1σ regions do not overlap fully and the cosmological constant case lies at the edge where the 1σ regions overlap. Numerically we get $w_0 = -1.28 \pm 0.23$, $w_1 = 0.569^{+0.865}_{-0.927}$ for the scale invariant case and $w_0 = -1.28 \pm 0.25$, $w_1 = 0.591^{+0.804}_{-0.881}$ with a running spectral index. We cut the $w_0 - w_1$ parameter space into four areas by the lines of $w_0 = -1$ and $w_0 + w_1 = -1$, quintessence, phantom, quintom A ($w_{DE}$ is phantom-like today but quintessence-like in the past) and quintom B (dark energy has $w_{DE} > -1$ today but $w_{DE} < -1$ at higher redshifts). Quintom A almost occupies the 1σ region. In a previous companion paper in the probe of dynamical dark energy, we got similar results where for the primordial spectrum part we included only $n_s$ and $A_s$ [40]. However inflation predicts a non-zero tensor contribution and it is a crucial parameter towards verifying the theory of inflation, in the current paper we consider $r$ contributions in cases where we do not simply assume a Harrison–Zel’’dovich spectrum.

In the probing of deviations from scale invariance and dynamical dark energy it is sometimes more intuitive to get constraints on the whole slopes of $n_s(k)$ and $w(z)$ on the relevant scales. We have got the constraints on $n_s(k)$ and $w(z)$ by using the covariance matrix of $n_s(k_0)$, $\alpha_s$ and $w_0$, $w_1$ from our MCMC results. In figures 3 and 4 we plot the constraints on $n_s(k)$ and $w(z)$ for the two different cases. In figure 3 it is obvious that
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Figure 2. 68% and 95% constraints on the dynamical dark energy model $w = w_0 + w_1(1 - a)$ marginalizing over the scale invariant primordial spectrum (blue dashed line) and over a primordial spectrum with a running spectral index (red solid line). In the latter case tensor contributions are included. The dotted lines stand for $w_0 \equiv -1$ and $w_0 + w_1 \equiv -1$.

Figure 3. 68% and 95% constraints on the slope of $n_s(k)$ from marginalizing over ΛCDM cosmology (left) and over the dynamical dark energy with equation of state $w = w_0 + w_1(1 - a)$ (right). The blue thick line stands for the scale invariant primordial spectrum.

the scale invariant primordial spectrum is more disfavoured in the case with dynamical dark energy, although it does allow more parameter space compared with the ΛCDM cosmology. It is intriguing that if we always start from ΛCDM cosmology in the probing of the primordial spectrum information, we might fail to find the true physics which is crucial for understanding inflation. Neglecting dark energy dynamics might lead to a bias in the probing of inflation, although the statistical significance is rather low.
Figure 4. 68% and 95% constraints on the evolution of the dynamical dark energy model $w = w_0 + w_1(1 - a)$ marginalizing over the scale invariant primordial spectrum (left) and over a primordial spectrum with a running spectral index (right). In the latter case tensor contributions are included.

In figure 4 we find that in both cases dynamical dark energy is favoured more than $1\sigma$ compared with the cosmological constant. It happens that in both cases $w_0 < -1$ is favoured more than $1\sigma$, as shown previously. The $1\sigma$ regions in figure 4 differ little when marginalizing over a scale invariant primordial spectrum and over a primordial spectrum with a running spectral index, which can also be easily understood from figure 2 and the minimum $\chi^2$ values in table 1. Our results here are somewhat similar to a previous analysis in [43]. The mild preference of dynamical dark energy over a cosmological constant rests mainly on the Riess sample of SNIa [11]. On the other hand such a preference also shows imprints on large scales of CMB multipoles via the integrated Sachs–Wolfe (ISW) effect and dark energy perturbations, which are correlated with $r$ and $\alpha_s$. Future improvements on the SNIa observations will also inversely help to probe the information of the primordial spectrum, as implied in our figures 1 and 3.

4. Summary and discussion

In this paper we have performed an analysis of global fitting allowing simultaneously the dynamics in both inflation and the dark energy sector. Our result shows that there is generically some correlation between the inflation and dark energy parameters and the parameter space is typically enlarged for the probing of dynamics in either sector compared to cases where one assumes there can be some dynamics in only one of these sectors. When we allow some dynamics in the dark energy sector we find interestingly that a deviation from scale invariant primordial spectrum is sightly more favoured by current cosmological observations than assuming a $\Lambda$CDM cosmology.

We should stress that starting from the theoretical aspects it is not so natural to predict exactly a constant running on $\alpha_s$ or $w_1$; on the other hand given the current precision

Reference [6] has done some similar analysis on this point, where different observational data sets have been used with somewhat different results. They did not include the effects of dark energy perturbations and study the constraints on dynamical dark energy with also $\alpha$ and $r$. In this paper we have tried to probe the deviation from scale variance and dynamical dark energy with equal weights.
of the observations and also for a generic study of the dynamics we are simply using some of the parametrizations on each sector. In general it is not so easy to achieve a precision cosmology [44], given the fact that for CMB (also LSS and lensing) on large scales we have the cosmic variance, on small scales we have the secondary effects which are non-negligible compared with the damped power itself and for LSS on small scales we have the not yet well-understood factor of bias and the complicated non-linear evolutions. And for SNIa the calibration is in some sense an open issue. Actually with our better understanding of the Universe and the developments of technology we are able to probe the Universe with more versatile observations with time going on. Nowadays we are also hoping to extract the information on the Universe through the observations from weak and strong lensing, radio galaxies, gamma-ray bursts (GRB), the Lyman-α forest (Lya) and the baryonic oscillations inherited in the LSS observations. However we also need to understand better their inherited systematics before we can extract more robust and precise information of our Universe. In this paper we have not considered small-scale CMB observations or those like Lya or GRB. We should point out that our fittings constitute only one of the data combinations and different combinations can certainly lead to somewhat different fitting results; on the other hand given the data set we use our results are robust.

Observing inflation and dark energy dynamics are among the most important aspects of the current cosmological research. Currently we are not yet able to detect the dynamics in either sector and in particular the possible contaminations of the CMB observations on the largest scales will affect our results qualitatively [45]. However our main concentration is on making a first detailed study in the probing of possible correlations between inflation and dark energy. If one starts always from the concordance ΛCDM cosmology one cannot achieve more subtle physics beyond that. And as we have shown in the cases where one assumes there is dynamics in only one of the sectors this can lead to some bias in our probe of the dynamics. If such a result can be confirmed at great significance by future observations, it will also shed light on the study of the inherent relationship between inflation and dark energy.

Recently the WMAP three-year data (WMAP3) have been released [46]–[50], with significant improvements on the quality [47]. The WMAP3 team claims a non-trivial preference of the red-tilted power spectrum, which is different from the first-year results and we can, one hopes, get some different fitting results. However our qualitative results depend strongly on the largest scales of CMB and as implied recently in [51] the pixel-based likelihood of WMAP3 on the largest scales seems to put too large a weight on the determination of cosmological parameters and one might incur the risk of getting biased; in the present paper we do not include the new WMAP3 data for a reanalysis and leave it for future investigations.

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