Constraining Slow-Roll Inflation in the Presence of Dynamical Dark Energy

Jun-Qing Xia and Xinmin Zhang
Institute of High Energy Physics, Chinese Academy of Science, P.O. Box 918-4, Beijing 100049, P. R. China
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In this paper we perform a global analysis of the constraints on the inflationary parameters in the presence of dynamical dark energy models from the current observations, including the three-year Wilkinson Microwave Anisotropy Probe (WMAP3) data, Boomerang-2K2, CBI, VSA, ACBAR, SDSS LRG, 2dFGRS and ESSENCE (192 sample). We use the analytic description of the inflationary power spectra in terms of the Horizon-flow parameters \( \{ \epsilon_i \} \). With the first order approximation in the slow-roll expansion, we find that the constraints on the Horizon-flow parameters are \( \epsilon_1 < 0.014 \) (95\% C.L.) and \( \epsilon_2 = 0.034 \pm 0.024 \) (1\( \sigma \)) in the \( \Lambda \)CDM model. In the framework of dynamical dark energy models, the constraints become obviously weak, \( \epsilon_1 < 0.022 \) (95\% C.L.) and \( \epsilon_2 = -0.006 \pm 0.039 \) (1\( \sigma \)), and the inflation models with a “blue” tilt, which are excluded about 2\( \sigma \) in the \( \Lambda \)CDM model, are allowed now. With the second order approximation, the constraints on the Horizon-flow parameters are significantly relaxed further. If considering the non-zero \( \epsilon_3 \), the large running of the scalar spectral index is found for the \( \Lambda \)CDM model, as well as the dynamical dark energy models.

I. INTRODUCTION

Inflation in the very early universe is the most attractive paradigm, which 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 the anisotropies of cosmic microwave background radiation (CMB). Inflation theory has successfully passed several non-trivial tests. The current cosmological observations are in good agreement with an adiabatic and scale invariant primordial spectrum, which is consistent with single field slow-roll inflation predictions. And the large angle anti-correlation is found in the temperature-polarization power spectrum, which is the signature of adiabatic superhorizon fluctuations at the time of decoupling [1].

In 1998, the analysis of the redshift–distance relation of type Ia supernova (SNIa) revealed the existence of the another 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 [2]. The nature of dark energy is among the biggest problems in modern physics and has been studied widely. The simplest candidate of dark energy is the cosmological constant (CC) however it suffers from the fine-tuning and coincidence problems [3]. To ameliorate these dilemmas some dynamical dark energy models such as Quintessence [4], Phantom [5] and K-essence [6].

Given our ignorance of the nature of dark energy, constraining the evolution of DE the equation of state (EoS) by cosmological observations is of great significance. Interestingly, there exists some hints that the EoS of dark energy has crossed over \( -1 \) at least once from current astronomical observations [7, 8], namely Quintom dark energy model, which greatly challenges the above mentioned dark energy models.

In 2006, the WMAP group [9] obtained the constraint on the scalar spectral index \( n_s = 0.958 \pm 0.016 \), which deviates from the simple scale-invariant primordial spectrum and disfavors the inflationary models with a “blue” tilt at more than 2\( \sigma \). Alternatively, the scale-invariant Harrison-Zel’dovich-Peebles (HZ) spectrum \( (n_s = 1, r = 0) \) is disfavored about 3\( \sigma \) [4]. And the large running of the scalar spectral index is still allowed [9, 10]. It seems that the scale-invariant spectrum is disfavored and the dynamics of Inflation has been detected. Similar results have also been found in the literature from the current observational data [11]. But it’s noteworthy that these analysis are based on the \( \Lambda \)CDM model. In the framework of dynamical dark energy models, the constraints on the inflationary parameters can be relaxed due to the degeneracy among the inflation and dark energy parameters [12, 13].

In this paper we use the current cosmological observations to carry out a first detailed study on the inflationary parameters in terms of the Horizon-flow parameters \( \{ \epsilon_i \} \) in the presence of dynamical dark energy models. Our results show that the dynamics of dark energy models weaken the constraints on the Horizon-flow parameters significantly.

II. METHOD AND DATA

In order to compare the theoretical predictions of inflation models with the cosmological observations, we often parameterize the primordial power spectra of scalar and tensor perturbations as:

\[
P_s(k) = A_s \exp \left( (n_s - 1) \ln \left( \frac{k}{k_*} \right) + \frac{\alpha_s}{2} \ln^2 \left( \frac{k}{k_*} \right) \right),
\]

where \( k_* \) is the scale where the power spectrum is normalized.
\[ P_t(k) = A_t \exp \left[ \frac{\alpha_t}{2} \ln^2 \left( \frac{k}{k_s} \right) \right], \tag{1} \]

where \( n_t \) is the spectral index, \( \alpha_t \) denotes the running of the spectral index and \( k_s \) is the pivot scale. In this paper we use the analytic description of the inflationary power spectra in terms of the Horizon-flow parameters \( \{ \epsilon_i \} \), which are based on the Hubble parameter during inflation and its derivatives, defined as \[14\]:

\[ \epsilon_1 = -\frac{\dot{H}}{H^2}, \quad \epsilon_{i+1} = \frac{d \ln |\epsilon_i|}{d N} = \frac{\epsilon_i}{H \epsilon_i} \quad (i \geq 1), \tag{2} \]

where \( N \) is the number of e-foldings. Following the Eq.\[11\], the power spectrum can be obtained as an expansion of the power spectrum in terms of the logarithmic wavenumber \[10\]:

\[ \ln \frac{P(k)}{P_0(k)} = b_0 + b_1 \ln \left( \frac{k}{k_s} \right) + b_2 \ln^2 \left( \frac{k}{k_s} \right) + \cdots, \tag{3} \]

where \( P_0 = H^2 G / \pi \epsilon_1 \), \( P_{i0} = 16 H^2 G / \pi \) and the coefficients \( b_i \) given in Ref.\[16\] are related to the Horizon-flow parameters \( \{ \epsilon_i \} \). The coefficients for the scalar spectrum are:

\[ b_{s0} = \frac{1}{2} \left( \frac{\pi^2}{2} - 2C - 7 \right) \epsilon_1 + \left( \frac{7 \pi^2}{12} - C^2 - 3C - 7 \right) \epsilon_1 \epsilon_2 \]
\[ + \left( \frac{\pi^2}{8} - 1 \right) \epsilon_2^2 + \left( \frac{\pi^2}{24} - \frac{C^2}{2} \right) \epsilon_2 \epsilon_3, \tag{4} \]

\[ b_{s1} = n_s - 1 = -2 \epsilon_1 - \epsilon_2 - 2 \epsilon_1^2 - (2C + 3) \epsilon_1 \epsilon_2 - C \epsilon_2 \epsilon_3, \tag{5} \]

\[ b_{s2} = \alpha_s = -2 \epsilon_1 \epsilon_2 - \epsilon_2 \epsilon_3, \tag{6} \]

and those for the tensor spectrum are:

\[ b_{t0} = \left( \frac{\pi^2}{2} - 2C - 7 \right) \epsilon_1 + \left( \frac{C^2}{2} - \frac{\pi^2}{8} - 1 \right) \epsilon_1 \epsilon_2, \tag{7} \]

\[ b_{t1} = n_t = -2 \epsilon_1 - 2 \epsilon_1^2 - (2C + 1) \epsilon_1 \epsilon_2, \tag{8} \]

\[ b_{t2} = \alpha_t = -2 \epsilon_1 \epsilon_2, \tag{9} \]

where \( C \equiv \ln 2 + \gamma_E - 2 \approx -0.7296 \) (\( \gamma_E \) is the Euler-Mascheroni constant). And the ratio of amplitudes of the scalar to the tensor at the pivot scale is:

\[ r = 16 \epsilon_1 \left[ 1 + C \epsilon_2 + \left( C + 5 - \frac{\pi^2}{2} \right) \epsilon_1 \epsilon_2 + \left( \frac{C^2}{2} - \frac{\pi^2}{8} + 1 \right) \epsilon_2^2 + \left( \frac{C^2}{2} - \frac{\pi^2}{24} \right) \epsilon_2 \epsilon_3 \right]. \tag{10} \]

At the first order approximation Eq.\[11\] becomes the well-known consistency relation of inflation \( r = -8 n_t \).

For dark energy, we choose the commonly used parametrization of the dark energy equation of state (EoS) as \[18\]:

\[ w_{\text{DE}}(a) = w_0 + w_1 (1 - a), \tag{11} \]

where \( a = 1 / (1 + z) \) is the scale factor and \( w_1 = -d w / d a \) characterizes the “running” of the equation of state (RunW henceforth). For comparison we also consider the ΛCDM model and the dark energy model with a constant equation of state (WCDM henceforth). When using the MCMC global fitting strategy to constrain the cosmological parameters, it is crucial to include dark energy perturbation \[9, 19, 20\]. However, it is divergent when the parameterized EoS crosses \( w = -1 \). By virtue of Quintom dark energy model \[7\], whose EoS can smoothly cross \( w = -1 \), the perturbation at the crossing points is continuous. Thus we have proposed a technique to treat dark energy perturbation in the whole parameter space, including \( w > -1, w < -1 \) and at the crossing points. For details of this method, we refer the readers to our previous companion papers \[20\].

\[1\] In the literature \[13\] the slow-roll parameters, \( \epsilon, \eta \) and \( \xi \), are also used to constrain the inflation models.

\[2\] Ref.\[17\] used the method of comparison equations in the study of the cosmological perturbations and obtained the similar coefficients \( b_i \).
TABLE I. Mean 1σ constraints on the cosmological parameters using the current observations. For columns I and II, the Horizon-flow parameters are obtained at the first and second order approximation in the slow-roll expansion respectively. For the weakly constrained parameters, ε1 and r, we quote the 95% upper limit instead.

| Parameter | ΛCDM | WCDM | RunW | ΛCDM | WCDM | RunW |
|-----------|------|------|------|------|------|------|
| 10^2ε1   | <1.39 | <2.18 | <2.21 | <2.72 | <3.10 | <3.11 |
| ε2       | 0.034 ± 0.024 | 0.004 ± 0.036 | −0.006 ± 0.039 | 0.131 ± 0.055 | 0.106 ± 0.063 | 0.094 ± 0.069 |
| ε2ε3     | 0      | 0    | 0    | 0.089 ± 0.042 | 0.089 ± 0.043 | 0.072 ± 0.044 |
| n_s      | 0.955 ± 0.019 | 0.977 ± 0.024 | 0.986 ± 0.028 | 0.905 ± 0.027 | 0.919 ± 0.033 | 0.926 ± 0.038 |
| α_s      | 0      | 0    | 0    | −0.092 ± 0.045 | −0.082 ± 0.045 | −0.075 ± 0.046 |
| r        | <0.223 | <0.349 | <0.354 | <0.391 | <0.457 | <0.458 |
| w_0      | −1     | −0.888 ± 0.064 | −1.02 ± 0.15 | −1     | −0.936 ± 0.078 | −1.02 ± 0.17 |
| w_1      | 0      | 0    | 0.474 ± 0.509 | 0.538 | 0    | 0.301 ± 0.632 |
| Δχ^2_{min} | 0     | −2.0     | −4.0     | 0    | −0.2     | −1.8 |

In this study, we have modified the publicly available Markov Chain Monte Carlo package CAMB\(^3\) / CosmoMC\(^4\) to include the dark energy perturbation and the public available code by Leach and Liddle for the primordial spectrum\(^5\). We assume purely adiabatic initial conditions and a flat universe. Our most general parameter space is:

\[ P ≡ (ω_b, ω_c, Θ_s, τ, w_0, w_1, ε_1, ε_2, ε_2ε_3, \log[10^{10}A_s]) \]

(12)

where \(ω_b ≡ Ω_b h^2\) and \(ω_c ≡ Ω_c h^2\) are the physical baryon and cold dark matter densities relative to the critical density, \(Θ_s\) is the ratio (multiplied by 100) of the sound horizon to the angular diameter distance at decoupling, \(τ\) is the optical depth to reionization, \(A_s\) is defined as the amplitude of the primordial spectrum. For the pivot scale of the primordial spectrum we set \(k_s = 0.05\) Mpc\(^{-1}\).

In the computation of CMB we have included the WMAP3 Temperature-Temperature (TT) and Temperature-Polarization (TE) power spectra with the routine for computing the likelihood supplied by the WMAP team \(^6\) as well as the smaller scale experiments, including Boomerang-2K2 \(^26\), CBI \(^27\), VSA \(^28\) and ACBAR \(^29\). For the Large Scale Structure information, we have used the Sloan Digital Sky Survey (SDSS) luminous red galaxy (LRG) sample \(^30\) and 2dFGRS \(^31\). To be conservative but more robust, in the fitting to the SDSS LRG sample we have used the first 15 bins only, 0.0120 < k_{eff} < 0.0998, which are supposed to be well within the linear regime. For SNIa we have marginalized over the nuisance parameter \(^32\). The supernova data we use are the ESSENCE (192 sample) data \(^33\). Furthermore, we make use of the Hubble Space Telescope (HST) measurement of the Hubble parameter \(H_0 ≡ 100h\) km s\(^{-1}\) Mpc\(^{-1}\) \(^34\) by multiplying the likelihood by a Gaussian likelihood function centered around \(h = 0.72\) and with a standard deviation \(σ = 0.08\). We also impose a weak Gaussian prior on the baryon density \(Ω_b h^2 = 0.022 ± 0.002\) (1σ) from Big Bang Nucleosynthesis \(^35\). Simultaneously we will also use a cosmic age tophat prior as 10 Gyr < t_0 < 20 Gyr.

For each regular calculation, we run 8 independent chains comprising of 150,000 – 300,000 chain elements. The average acceptance rate is about 30%. We test the convergence of the chains by Gelman and Rubin criteria \(^36\) and find \(R - 1\) is of order 0.01 which is more conservative than the recommended value \(R - 1 < 0.1\).

III. RESULTS

We summarize our main global fitting results in Table I. Table I lists all of the relevant one-dimensional median values and 1σ constraints. Shown together are the corresponding reduction of \(χ^2_{min}\) values compared with the ΛCDM model. For the constraints on \(ε_1\) and \(r\) only 2σ upper bounds have been shown.

Firstly we consider the first order approximation in the slow-roll expansion, where the relevant parameters are \(ε_1\) and \(ε_2\). In this case the running of the spectral index vanishes. In the ΛCDM model, illustrated in the left up panel

\(^3\) http://camb.info/.
\(^4\) http://cosmologist.info/cosmomc/.
\(^5\) http://astronomy.sussex.ac.uk/~sleach/inflation/camb_inflation.html/.
FIG. 1: Constraints on the inflationary parameters at first order in the slow-roll approximation in the ΛCDM (blue dash-dotted lines), WCDM (red dash lines) and RunW (black solid lines) dark energy models respectively. The left up panel and right down panel are the one dimensional marginalized distribution of Horizon-flow parameters $\epsilon_1$ and $\epsilon_2$. The left down panel gives the two dimensional constraint on $(\epsilon_2, \epsilon_1)$. And the right up panel gives the two dimensional constraint on $(n_s, r)$. The contours stand for the 68% and 95% confidence level. The two solid magenta lines delimit the three classes of inflation models, namely, small-field, large-field and hybrid models. The blue points are predicted by $m^2\phi^2$ model and $\lambda\phi^4$ model respectively with the number of e-foldings, $N$, being $50 - 60$ for $m^2\phi^2$ model and 64 for $\lambda\phi^4$ model.

and right down panel of Fig.1 we obtain the constraints on the Horizon-flow parameters are $\epsilon_1 < 0.014$ (95% C.L.) and $\epsilon_2 = 0.034 \pm 0.024$ (1σ) and consequently with Eq. (5) and Eq. (10) we obtain the spectral index $n_s = 0.955 \pm 0.019$ (1σ) and the tensor-to-scalar ratio $r < 0.223$ (95% C.L.), which is in good agreement with the WMAP’s results [9].

From the right up panel of Fig.1 one can see that a pure HZ spectrum for scalar perturbations with no tensors ($n_s = 1$, $r = 0$) is clearly disfavored at more than 2σ by the current observations. We plot the same constraints in terms of the Horizon-flow parameters $\epsilon_1$ and $\epsilon_2$ in the left down panel of Fig.1. For the simple monomial chaotic models, the single slow-rolling scalar field with potential $V(\phi) \sim m^2\phi^2$, which predicts $(n_s, r) = (1 - 2/N, 8/N)$, is well within 1σ region, while another single slow-rolling scalar field with potential $V(\phi) \sim \lambda\phi^4$, which predicts $(n_s, r) = (1 - 3/N, 12/N)$, is excluded by more than 2σ in the ΛCDM model [30, 38, 39, 40].

However, the current observational data don’t exclude the dynamical dark energy models and especially mildly favor a class of models with EoS across the cosmological constant boundary $\frac{1}{3}$. Due to the degeneracy between inflation and dark energy, it’s necessary to perform an analysis of global fitting allowing simultaneously the dynamics in both inflation and the dark energy sector.

In the framework of dynamical dark energy models, we find that the constraints on the Horizon-flow parameters $\epsilon_1$ and $\epsilon_2$ and the derived parameters $n_s$ and $r$ have been weakened dramatically as shown in the one dimensional distribution plots of Fig.1. Quantitatively, the constraints on the Horizon-flow parameters are $\epsilon_1 < 0.022$ (95% C.L.) for both models and $\epsilon_2 = 0.004 \pm 0.036$ (1σ) for WCDM model, $\epsilon_2 = -0.006 \pm 0.039$ (1σ) for RunW model. And constraints on the derived parameters are $n_s = 0.977 \pm 0.024$ (1σ) for WCDM model, $n_s = 0.986 \pm 0.028$ (1σ) for RunW model, and $r < 0.35$ (95% C.L.) for both models. The mean value of $n_s$ gets closer to $n_s = 1$ and the 95% confidence level constraints on the dynamics of Inflation in the $(\epsilon_2, \epsilon_1)$ plane straightforwardly.

\[ \text{Ref. [37]} \]
upper limit of \( r \) is relaxed due to the degeneracy that the tensor fluctuation and the dark energy component, through the ISW effect, mostly affect the large scale (low multipoles) TT power spectrum of CMB [12, 13, 44].

Because of this degeneracy, in the two dimensional plot of Fig.1, we can find that the allowed parameter space is enlarged dramatically. Consequently the HZ spectrum, disfavored about 3\( \sigma \) in the \( \Lambda \)CDM model, can be allowed within the 2\( \sigma \) region in the presence of the dynamics of dark energy. And interestingly many hybrid inflation models, excluded in the \( \Lambda \)CDM model, revive in the framework of dynamical dark energy models as illustrated in Fig.1 [13].

![FIG. 2: Marginalized posterior probability distributions for the Horizon-flow parameters, \( \epsilon_1 \), \( \epsilon_2 \) and \( \epsilon_2 \epsilon_3 \), and the derived inflationary parameters, \( n_s \), \( \alpha_s \) and \( r \), up to second order approximation in the slow-roll expansion in the \( \Lambda \)CDM (blue dash-dotted lines), WCDM (red dash lines) and RunW (black solid lines) dark energy models respectively.](image)

With the second order approximation in the slow-roll expansion, one has to consider the third Horizon-flow parameter \( \epsilon_3 \). In our calculation we choose \( \epsilon_2 \epsilon_3 \) as the basic parameter directly instead of \( \epsilon_3 \). Practically this will make our numerical calculation much more efficient. And we notice that the second order formalism are valid in the limit of \( \epsilon_2 \epsilon_3 \ll 1 \), but not \( \epsilon_3 \ll 1 \) [39, 45]. We have also checked with \( \epsilon_3 \) as a parameter in the fitting and found the constraint is very poor [24, 39, 40].

In Fig.2, we show the one dimensional marginalized posterior probability distributions for the Horizon-flow parameters, \( \epsilon_1 \), \( \epsilon_2 \) and \( \epsilon_2 \epsilon_3 \), and the derived inflationary parameters, \( n_s \), \( \alpha_s \) and \( r \), up to second order approximation in the slow-roll expansion. The constraints on the Horizon-flow parameters become weaken obviously in the dynamical dark energy models relative to the \( \Lambda \)CDM model.

Another result is the appearance of large running of scalar spectral index which has been found in the literature [9, 10]. From the current observations, illustrated in Fig.2, we obtain the fully marginalized value of \( \epsilon_2 \epsilon_3 \) and \( \alpha_s \):

\[
\epsilon_2 \epsilon_3 = 0.089 \pm 0.042, \quad \alpha_s = -0.092 \pm 0.045,
\]

which deviate from zero with more than 2\( \sigma \), in the \( \Lambda \)CDM model. This large value of running \( \alpha_s \) violates the inequality:

\[
|n_s - 1| \gg \left| \frac{\alpha_s}{2} \ln \left( \frac{k}{k_*} \right) \right|,
\]  

for \( k \) far away from the pivot scale \( k_* \). One possible explanation is that current observations are not accurate enough to determine the scalar spectral index yet. This large running needs much more observation data, such as PLANCK measurement [13], to verify. Indeed, these constraints may be affected by the Lyman-\( \alpha \) forest data [41]. However, if this large value of running \( \alpha_s \) can be confirmed by the future measurement, this would be a great challenge to the single-field inflation model described by the slow roll expansion which can not produce this large, negative running of scalar spectral index \( \alpha_s \) [42]. At that time, two or more Inflationary history or breaking down the slow roll expansion would be needed [43].

In the framework of dynamical dark energy models, the large running of scalar spectral index is still allowed. The constraints on \( \alpha_s \) are \( \alpha_s = -0.082 \pm 0.045 \) and \( \alpha_s = -0.075 \pm 0.046 \) for the WCDM and RunW models respectively. The mean value of \( \alpha_s \) slightly shift and the error bars are unchanged. It seems that the correlation between dark energy parameters and the running \( \alpha_s \) is weak [13, 14]. This weak correlation might be understood from the distinct effects on CMB TT power spectrum. For the dark energy parameters \( w_0 \) and \( w_1 \), the effect on CMB TT power
spectrum can be somewhat identified with a constant effective equation of state [46]:

\[ w_{\text{eff}} \equiv \frac{\int da \Omega(a) w(a)}{\int da \Omega(a)} \tag{14} \]

Keeping other cosmological parameters unchanged, the TT power spectrum will be shifted to larger scalar if the effective EoS \( w_{\text{eff}} \) becomes larger. However, the negative running \( \alpha_s \) will suppress the amplitude of the spectrum, which cannot be mimicked by adjusting the dark energy parameters only. This may be the reason of the weak correlation between the dark energy parameters and the running of scalar spectral index \( \alpha_s \).

IV. SUMMARY

In this paper we perform an analysis of global fitting on the inflationary parameters in terms of the Horizon-flow parameters \( \{ \epsilon_i \} \) in the presence of dynamical dark energy models from the current observations. Our analysis shows that the dynamics of dark energy generally weakens the constraints on inflationary parameters, due to the degeneracy between dark energy and inflation parameters.

With the first order approximation in the slow-roll expansion, the constraints on \( \epsilon_1 \) and \( \epsilon_2 \) can be significantly relaxed and the allowed parameter space of \( (\epsilon_2, \epsilon_1) \), \( (n_s, r) \) panels are enlarged relative to the \( \Lambda \)CDM model. Consequently the HZ spectrum \( (n_s = 1, r = 0) \), disfavored about 3\( \sigma \) in the \( \Lambda \)CDM model, can be allowed within 2\( \sigma \) in the presence of the dynamics of dark energy. Interestingly many hybrid inflation models, especially for models with a “blue” tilt \( (n_s > 1) \), excluded in the \( \Lambda \)CDM model, revive in the framework of dynamical dark energy models.

With the second order approximation in the slow-roll expansion, we use the parameter \( d\epsilon_2/dN = \epsilon_2 \epsilon_3 \) to do the calculations instead of \( \epsilon_3 \). We find that the constraints on the Horizon-flow parameters become weakened further and the large running of scalar spectral index is still allowed, in the framework of dynamical dark energy models. The degeneracy between the running of the scalar spectral index and the dynamics of dark energy is weak.

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