Testing Oscillating Primordial Spectrum and Oscillating Dark Energy with Astronomical Observations

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In this paper we revisit the issue of determining the oscillating primordial scalar power spectrum and oscillating equation of state of dark energy from the astronomical observations. By performing a global analysis with the Markov Chain Monte Carlo method, we find that the current observations from five-year WMAP and SDSS-LRG matter power spectrum, as well as the “union” supernovae sample, constrain the oscillating index of primordial spectrum and oscillating equation of state of dark energy with the amplitude less than $|n_{amp}| < 0.116$ and $|w_{amp}| < 0.232$ at 95\% confidence level, respectively. This result shows that the oscillatory structures on the primordial scalar spectrum and the equation of state of dark energy are still allowed by the current data. Furthermore, we point out that these kinds of modulation effects will be detectable (or gotten a stronger constraint) in the near future astronomical observations, such as the PLANCK satellite, LAMOST telescope and the currently ongoing supernovae projects SNLS.

I. INTRODUCTION

Recent advances in observational cosmology have revealed that our universe has experienced at least 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. This can naturally explain why the universe is flat, homogeneous and isotropic. Inflation is driven by a potential energy of a scalar (or multi-scalar) 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). The other one is accelerating expansion driven by dark energy (DE) which dominates the energy density of the universe currently. Understanding the nature of dark energy is among the biggest problems in modern physics and has been studied actively in the literature.

At present, the high quality observational data, CMB\textsuperscript{[1, 2, 3]}, LSS\textsuperscript{[4]} and type Ia supernovae (SN Ia)\textsuperscript{[5]} and so on, have provided the stringent constraints on cosmological parameters. For example, current data can constrain the primordial scalar power spectrum index $n_s$ and the energy density of dark energy component $\Omega_{de}$ to 1\% level\textsuperscript{[6]}. Besides the current observations, there are many ongoing projects, such as PLANCK\textsuperscript{[7]}, LAMOST\textsuperscript{[8]} and SNLS\textsuperscript{[9]}. These projects will provide more accurate measurements on CMB temperature anisotropies and polarization, LSS matter power spectrum and the luminosity distance, which will be helpful for studies of inflation and dark energy and determinations of cosmological parameters.

Generally, the current data analysis bases on the simple parameterizations of the primordial power spectrum and the equation of state (EoS) of DE. However, we note that some inflation models can generate the power spectrum with some modulated wiggles. This picture can be realized by the inflaton field with a step function of the potential\textsuperscript{[10, 11]} or oscillating potential\textsuperscript{[12]}. The effects from the Trans-Planckian initial condition can also lead to oscillations which do imprint directly on the primordial scalar power spectrum\textsuperscript{[13, 14, 15]}. The bouncing model driven by the Quintom\textsuperscript{[16]} matter can also give rise to some wiggles in the primordial scale-invariant power spectrum, because in this model the universe initially experiences a contracting stage, after the contracting phase it bounces to an inflationary phase, therefore the primordial fluctuations in sub-hubble region would deviate from that generated in Bunch-Davies vacuum\textsuperscript{[17]}. The Quintom bounce provide a solution to initial singularity problem, and in this scenario there’s no Trans-Planckian problem since we can choose the initial condition via contracting phase. The featured primordial scalar perturbation spectrum with local bumps are studied in Ref.\textsuperscript{[18]}.

In some sense, the study for DE is similar to inflation, either in model building or data fitting. The featured EoS of DE, especially the oscillatory behavior EoS can provide us an unconventional evolution of universe. Observationally, these kinds of modulated EoS will leave clue on the hubble diagram or the matter power spectrum as well as the temperature power spectrum of CMB, which give us some hints to test such a scenario. The periodic oscillatory EoS can be realized by the two scalar field Quintom matter\textsuperscript{[19]}. And in Ref.\textsuperscript{[20]}, a class of Quintom models with an oscillating equation of state have been studied. In such a scenario, the early inflation and the current acceleration of the universe can be unified, the scale factor keeps increasing from one period to another and leads naturally to a highly flat universe. The periodic recurs will not lead to big crunch nor big rip and the coincidence problem can be reconciled by the vicissitudinary repetition. Also, the studied relevant to these kind of oscillating DE can be found in \textsuperscript{[21, 22, 23, 24]}.
Given the above progress in the astronomical observations and physical motivations, it can potentially lead us to study issues related to the featured structure of primordial spectrum and the EoS of DE. In this paper, we aim to study the constraints on such kind of featured parametrization of the primordial spectrum as well as the EoS of DE. We perform the global fitting by using the Markov Chain Monte Carlo method with the current data from CMB, LSS and SN, and also from the simulated future projects, such as PLANCK, 5-year Supernovae Legacy survey (SNLS) and LAMOST.

The paper is organized as follows: In section II we introduce the method of fitting and data we used in our analysis. The results and discussions are given in section III. The last section is on the summary.

II. METHOD AND DATA

As mentioned before, there are many theoretical models which can provide the non-trivial structure on the primordial power spectrum and EoS of DE. In order to study the oscillating primordial scalar power spectrum independent of the specific model, we parameterize the power spectrum $P_\chi$ as:

$$\ln P_\chi(k) = \ln A_s(k) + \left[n_{s0}(k_0) - 1\right] \ln \left(\frac{k}{k_0}\right) - \frac{\text{amp}}{n_{\text{fre}}} \cos \left(n_{\text{fre}} \ln \left(\frac{k}{k_0}\right)\right),$$  

where, $A_s$ is the amplitude of primordial power spectrum, $k_0$ is the scale pivot and is set as 0.05 Mpc h$^{-1}$. $n_{s0}$ characterizes the tilt of spectrum while $\text{amp}$ and $n_{\text{fre}}$ denote the contribution of featured oscillation. Comparing with the traditional definition of spectral index, we get

$$n_s = \frac{d \ln P_\chi(k)}{d \ln k} = n_{s0} + \text{amp} \sin \left(n_{\text{fre}} \ln \left(\frac{k}{k_0}\right)\right),$$

and one can find that for small $n_{\text{fre}}$, this parametrization goes back to the traditional form, i.e. the last term in the right hand side of equation above gives rise to the running of the scalar spectral index.

For the parametrization of DE, we take the form given in [25]:

$$w(a) = w_0 + \text{amp} \sin [w_{\text{fre}} \ln(a)].$$

This oscillating behavior in the EoS can lead to the modulations on the Hubble diagram or a recurrent universe which unifies the early inflation and the current acceleration. In Refs. [21, 22, 26, 27] some preliminary studies have been presented on this kind of DE model. We noticed that there are some hints on the oscillating behavior for example as shown in the Fig. 10 of the SNIa paper [28] and see also paper in Ref. [29]. Our sine function has the advantage of preserving the oscillating feature of the DE EoS at high redshift measured by the CMB data. For simplicity and focusing on the study at lower redshift, we set $w_{\text{fre}}$ to be $3\pi/2$ in order to allow the EoS to evolve more than one period within the redshift range of $z = 0$ to $z = 2$, where the SNIa data are most robust. For the $\Lambda$CDM model, $w_0 = -1$ and $\text{amp} = 0$.

We extend the publicly available MCMC package CosmoMC$^1$[30] by including dark energy perturbation[31], and we assume the adiabatic initial condition in our calculation. The most general parameter space is:

$$\mathbf{P} \equiv (\omega_b h^2, \omega_c h^2, \Theta_s, \tau, w_0, \text{amp}, n_{s0}, n_{\text{amp}}, n_{\text{fre}}, A_s),$$

where $\omega_b \equiv \Omega_b h^2$ and $\omega_c \equiv \Omega_c h^2$ with $\Omega_b$ and $\Omega_c$ being 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 re-ionization, $w_0$ and $\text{amp}$ are the EoS parameters of DE, and $n_{s0}$, $n_{\text{amp}}$, $n_{\text{fre}}$, $A_s$ are the parameters related to the primordial scalar power spectrum in Eq. (1).

In our calculations, we take the total likelihood to be the products of the separate likelihoods ($\mathcal{L}_i$) of CMB, LSS and SNIa. Defining $\chi^2_{L,i} \equiv -2 \log \mathcal{L}_i$, we then have

$$\chi^2_{L,\text{total}} = \chi^2_{L,\text{CMB}} + \chi^2_{L,\text{LSS}} + \chi^2_{L,\text{SNIa}}.$$  

If the likelihood function is Gaussian, $\chi^2_{L}$ coincides with the usual definition of $\chi^2$ up to an additive constant corresponding to the logarithm of the normalization factor of $\mathcal{L}$.

$^1$ Available at: \url{http://cosmologist.info/cosmomc/}
The data used for current constraints include the five-year WMAP (WMAP5) [1] as well as some small-scale CMB measurements, such as CBI [2], VSA [3], BOOMERanG [32] and the newly released ACBAR data [33]. For the Large Scale Structure information, we use the Sloan Digital Sky Survey (SDSS) luminous red galaxy (LRG) sample [34]. The supernovae data we use are the recently released “Union” compilation of 307 samples [5]. In the calculation of the likelihood from SN Ia we marginalize over the relevant nuisance parameter [35]. Furthermore, we make use of the Hubble Space Telescope (HST) measurement of the Hubble parameter $H_0 = 100h$ km s$^{-1}$ Mpc$^{-1}$ [36] by multiplying the likelihood by a Gaussian likelihood function centered around $h = 0.72$ and with a standard deviation $\sigma = 0.08$. We also impose a weak Gaussian prior on the baryon density $\Omega_b h^2 = 0.022 \pm 0.002$ (1 $\sigma$) from the Big Bang Nucleosynthesis [37], and a cosmic age tophat prior as 10 Gyr $< t_0 < 20$ Gyr.

For the future data, we consider the measurements of LSS from LAMOST [8], the CMB from PLANCK [7] and the SN Ia from 5-year SNLS [9]. For more information about the mock data, we refer to [25, 38].

For the simulation of LAMOST, we mainly consider the 3D matter power spectrum of galaxies. The simulated error of the matter power spectrum including the statistical errors due to sample variance and shot noise are given by

$$\sigma_P^2(P) = 2 \times \frac{(2\pi)^3}{V} \times \frac{1}{4\pi k^2 \Delta k} \times (1 + \frac{1}{\bar{n} P^2}),$$

where $V$ is the survey volume and $\bar{n}$ is the mean galaxy density. In our simulations, we set the redshift of the LAMOST main sample to be $z \sim 0.2$, and the survey area to be 15000 deg$^2$. The total number of galaxies within the survey volume is $10^7$ [8]. The maximum $k$ we consider is $k \sim 0.1 h$ Mpc$^{-1}$. For the simulation with PLANCK, we follow the method given in our previous paper [25]. We mocked the CMB TT, EE and TE power spectrum by assuming the certain fiducial cosmological model. For the detailed techniques, we refer to our previous paper [25]. We have also simulated 500 SN Ia according to the forecast distribution of the SNLS [10]. For the error, we follow the Ref. [41] which takes the magnitude dispersion 0.15 and the systematic error $\sigma_{sys} = 0.02 \times z/1.7$. The whole error for each data is given by:

$$\sigma_{maga}(z_i) = \sqrt{\sigma_{sys}(z_i)^2 + 0.15^2 n_i},$$

where $n_i$ is the number of supernova of the $i$’th redshift bin. We take $\Lambda$CDM model as the fiducial model in simulating the data.

III. NUMERICAL RESULTS

A. Oscillating Primordial Power Spectrum

The oscillating behavior of the primordial spectral index will imprint on CMB and LSS via the following two equations:

$$P_n(k) = T^2(k)P_X(k),$$

$$C_l = \frac{4\pi}{2l+1} \int dk k T_l^2(k)P_X(k),$$

where $T(k)$ and $T_i(k)$ are the transfer functions which describe perturbation evolution of matter and photon from reheating era up to now [42, 43]. Based on the parametrization in Eq. [1], in Fig. [1] we display the matter power spectrum $P_n(k)$ and the TT power spectrum $C_l$. The parameters are chosen to be $[n_s, n_{amp}, n_{f, re}]=[0.96, 0.10, 3.0]$, which can fit the current observational data at 2$\sigma$ C.L.. The blue solid lines are given by the specific oscillatory power index, while the ordinary smooth parametrization are given by the red dashed lines. One can find the modulated oscillating structure in the whole linear regime of the matter power spectrum, and this scenario as well as the related theoretical model has been considered in Ref. [12]. Unlike Trans-Plankian mechanism or step-like models which just give a local feature in the $k$ space, this kind of signature has effects in the whole linear regime, however it might not be easy to distinguish from baryon acoustic oscillation in small scales. From Fig. [1] one can see the effects on CMB TT power spectrum with the change of the amplitude of the Doppler peaks. In short, these distinct hints on the observations will feed back constraints on the parameters.

In Table I we give the main results of our numerical calculation. We present the 1, 2$\sigma$ constraints from the current data which include WMAP5, SDSS-LRG matter power spectrum as well as the “union” SN Ia data. We also provide
FIG. 1: Primordial power spectrum (top left), matter power spectrum (top right) and CMB TT power spectrum (bottom) of the smooth parametrization (i.e. parameterized by a power law with $n_s = 0.96$ and $\alpha_s = 0$) (red) and oscillating parametrization (blue). The oscillating parameters are $[n_{a0}, n_{amp}, n_{fre}]= [0.96, 0.10, 3.0]$ which are within $1 \sigma$.

Table I: Constraints on the cosmological parameters from the current and future observations. Here we show the mean values and 1, 2$\sigma$ error bars. For the future measurements, we give the standard deviation of these parameters. For some parameters that are only weakly constrained we quote the 95% upper limit.

| Parameter  | Current Constraints                 | Future Constraints |
|------------|-------------------------------------|--------------------|
| $n_{a0}$   | $0.974 \pm 0.016 \pm 0.033$        | 0.003              |
| $n_{amp}$  | $0.0 \pm 0.066 \pm 0.116$         | 0.028              |
| $n_{fre}$  | $< 6.256$                          | $< 1.651$          |
| $W_0$      | $-0.968 \pm 0.098 \pm 0.230$       | 0.040              |
| $w_{amp}$  | $0.030^{+0.130}_{-0.270}$         | 0.140              |

the constraints from the simulated PLANCK TT, TE and EE power spectrum, the LAMOST matter power spectrum and the 5-year SNLS data. For the future constraints, we mainly give the standard deviation.

In Fig. 2 we give the 1-D probability distribution of $n_{a0}$, $n_{amp}$ and $n_{fre}$. The black solid line is the constraints from the current observational data. We get $n_{a0} = 0.974 \pm 0.016(1\sigma)$, and also the constraints on the amplitude of the power index $|n_{amp}| < 0.116$ at 95% confidence level. The scale invariant power spectrum is within 2$\sigma$ C.L., but the constraints on the frequency of power index is still very weak, namely, the 2$\sigma$ upper limit is $n_{fre} < 6.256$. Therefore, the current data still allow the oscillating structures on the primordial scalar spectrum.

Since the present data do not give very stringent constraints on the parameters, it is worthwhile discussing whether future data could determine these parameters conclusively. From the Table I one can see that the constraints get tightened significantly. The standard deviation of $n_{a0}, n_{amp}$ are 0.003 and 0.028 respectively, while the 2$\sigma$ upper limit of $n_{fre}$ is 1.651. Since mocked data are generated from the fiducial model with the standard power-law primordial spectrum, the best fit values of $n_{amp}$ and $n_{fre}$ are expected to be around zero. With this simulation, we find the scale invariant power spectrum can be tested at 8$\sigma$ C.L., and the error of the oscillating amplitude can be shrunk by
a factor of 2.35.

B. Oscillating dark energy

The main contribution of dark energy on CMB is on the geometrical angular diameter distance to the last scattering surface. The oscillating EoS can also modulate the TT power spectrum as well as the matter power spectrum, since oscillating EOS of DE can leave somewhat similar imprints as oscillating primordial spectrum. For the evolution of EoS given in Eq. (3), when $w_0$ deviates significantly from $-1$ and $w$ is matter-like, the contributions to large scale CMB are significant due to the Integrated Sachs-Wolfe (ISW) effects.

Firstly, with current data, we get $w_0 = -0.958 \pm 0.098$, $w_{\text{amp}} = 0.030^{+0.124}_{-0.130}$ at 68% confidence level, however, $\Lambda CDM$ remains a good fit.

In Fig. 2 we display the two dimensional cross-correlated constraints and one dimensional probability distribution of $w_0$ and $w_{\text{amp}}$. The black solid lines are from the current data sets. For the future simulated data, the $w_0$ will be constrained tightly, however $w_{\text{amp}}$ gets broaden a little bit, which is due to the degeneracy between the $w_0$ and the $w_{\text{amp}}$. Quantitatively, the future simulated data shrinks the error bar of $w_0$ by a factor of 2.4 as delineated by the blue dashdot lines. And interestingly, it also rotates the contour in the $w_0$-$w_{\text{amp}}$ plane. To understand this phenomenon we notice that physics which is interesting to us is the possible deviation of the $w$ from $w = -1$. In our parametrization, $w_0 + w_a$ gives the largest value for this deviation. In Fig. 4 we plot the 1-D probability distribution of $w_0 + w_a$. From this figure one can see indeed the future data give a tighter constraint.

Finally, in figure 5 we present the one dimensional constraint on the evolution of $w(z)$ from the current data. One can see from this figure $\Lambda CDM$ remains a good fit, however the dynamical models with oscillated feature are not excluded.

IV. SUMMARY

In this paper we have studied the signature of the modulated primordial scalar power spectrum and the oscillating EoS of DE in the observations, such as CMB, LSS and SN Ia. Based on the parameterizations of $n_s(k)$ and $w(z)$ in Eq. (2) and Eq. (3), we firstly present the constraints with the current observations. Furthermore, we consider the constraints from the future astronomy surveys, for example, the future CMB project PLANCK, the LAMOST telescope and 500 SN from the coming 5 year SNLS.

Our results show that the current data have put constraints on the featured primordial scalar power spectrum scenario, however, the limits are rather weak. From global data analysis, we get $n_{s,0} = 0.974 \pm 0.016$ which indicates a red power spectrum consistent with our previous analysis. Within 2σ C.L., with the current observations we have $|n_{\text{amp}}| < 0.116$ and $n_{\text{f,rc}} < 6.256$, and for the future observations, the error bar can be shrunk significantly.

On the other hand, for the constraints on DE, we find the oscillating EoS of DE can fit the current data well, as well as the $\Lambda CDM$ model. The amplitude of the oscillation of EoS are limited to be $|w_{\text{amp}}| < 0.232$ at 95% confidence
FIG. 3: One-dimensional constraints on the $w_0$(bottom right panel) and $w_{\text{amp}}$(top panel). The black solid lines are given by current data, the blue dashdot lines are given by mocked data:SNLS+PLANCK+LAMOST.

FIG. 4: One-dimensional constraints on the $w_0 + w_{\text{amp}}$. Different colored line represents different datasets used as before.

FIG. 5: Constraints on $w(\alpha) = w_0 + w_{\text{amp}} \sin[\frac{3\pi}{2} \ln(\alpha)]$ from the current observations. Median value (central red dotted line), 68% (area between black solid lines) intervals are shown. The red dotted line is the cosmological constant boundary.
level. The future data will give a stronger constraint, especially on the $w_0$ parameter.

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