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# Primordial power spectrum features in phenomenological descriptions of inflation

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ABSTRACT

We extend an alternative, phenomenological approach to inflation by means of an equation of state and a sound speed, both of them functions of the number of $e$-folds and four phenomenological parameters. This approach captures a number of possible inflationary models, including those with non-canonical kinetic terms or scale-dependent non-gaussianities. We perform Markov Chain Monte Carlo analyses using the latest cosmological publicly available measurements, which include Cosmic Microwave Background (CMB) data from the Planck satellite. Within this parameterization, we discard scale invariance with a significance of about $10\sigma$, and the running of the spectral index is constrained as $\alpha_s = -0.60^{+0.08}_{-0.10} \times 10^{-3}$ (68% CL errors). The limit on the tensor-to-scalar ratio is $r < 0.005$ at 95% CL from CMB data alone. We find no significant evidence for this alternative parameterization with present cosmological observations. The maximum amplitude of the equilateral non-gaussianity that we obtain, $|f_{NL}^{equil}| < 1$, is much smaller than the current Planck mission errors, strengthening the case for future high-redshift, all-sky surveys, which could reach the required accuracy on equilateral non-gaussianities.


## 1. Introduction

Inflation is the leading and most attractive theory, with observational success, capable of describing the initial conditions of the universe while solving the main problems of the standard Big Bang Cosmology [1–3]. Usually inflation is described via the dynamics of a single new scalar degree of freedom, the inflaton, coupled to Einstein Gravity and slowly-rolling down a potential. The validity of the proposed inflationary potential relies on its predictions for the standard inflationary observables: the tensor-to-scalar ratio $r$, characterizing the amplitude of the gravitational waves produced during inflation, the scalar spectral index $n_s$, measuring the scale dependence of the power spectrum $P_\zeta(k)$, its running $\alpha_s$ and possibly, the running of the running $\beta_s$. However there is a plethora of theoretical models belonging to this type of scenario, *i.e.* of inflationary potentials, that could give predictions of the inflationary observables that are in good agreement with current Cosmic Microwave Background (CMB) measurements [4]. According to these observations, structures grow from Gaussian and adiabatic primordial perturbations.

However, another probe of the mechanism of the inflationary physics comes from the study of non-Gaussian components of the primordial fluctuations [5]. These contributions are characterized by the three-point correlation function of the primordial curvature perturbations $\zeta$ or its Fourier transform, the bispectrum $B_\zeta(k)$. It is well known that a detectable large amount of non-gaussianities would rule out the standard single-field slow-roll scenarios [6,7], leading to the study of exotic inflationary models or even theories with different dynamics for the generation of primordial perturbations. The amount of non-gaussianities is characterized by the observable $f_{NL}$ defined as $\zeta(\mathbf{x}) = \zeta_g(\mathbf{x}) + f_{NL}^{local}(\zeta_g(\mathbf{x})^2 - \langle\zeta_g(\mathbf{x})^2\rangle)$, where $\zeta_g$ is the primordial Gaussian curvature perturbation [8,9]. Recent measurements from Planck CMB polarization data have set the limits $f_{NL}^{local} = 0.8 \pm 5.0$, $f_{NL}^{equil} = -4 \pm 43$ and $f_{NL}^{ortho} = -26 \pm 21$ with 68% CL errors [10].

In general, there are inflationary models in which the value of the sound speed of the primordial curvature perturbation, $c_s$, can be different from that of the speed of light.[1] These models are characterized by allowing non-canonical kinetic terms in the Lagrangian (see, *e.g.*, [11] and references therein). Theoretically, it is possible to derive a limit in the sound speed as a function of

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[1] In single-field slow-roll inflation $c_s = 1$.

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the tensor-to-scalar-ratio, provided that $c_s$ is constant [12]. Models in which not only the sound speed is non-standard (*i.e.* $c_s \neq 1$) but also varies with time, such as in Dirac–Born–Infeld (DBI) inflation [13–15], lead to an amplitude $f_{\rm NL}$ of the primordial bispectrum which is scale-dependent [16,17]. A varying sound speed, $c_s = c_s(\tau)$, during the inflaton evolution can imprint features in both the matter power spectrum and bispectrum ($P_\zeta(k)$ and $B_\zeta(k)$, respectively) [18,19], see Ref. [20] for an extensive review.[2] These signatures can be constrained using cosmological data and, therefore, studying them also helps as a discriminator of the inflationary mechanisms.

In this work we adopt the phenomenological description of inflation from [47] in which both the equation of state and the sound speed are parameterized as a function of the number of *e*-folds $N$. The usual inflationary parameters, *i.e.* tensor-to-scalar ratio $r$, the scalar spectral index $n_s$ and its running $\alpha_s$, are derived quantities and will also depend on $N$. As we shall illustrate in the following, this model generates features in the primordial power spectrum. The deviations from the standard $P_\zeta(k)$, due to the variation of the sound speed, and the generated amplitude of the bispectrum, $f_{\rm NL}$, will be exploited to constrain this phenomenological approach to inflation.

The structure of the paper is as follows. Section 2 describes the parameterization used in this study. In Section 3 we use the available tools to compute the features in the primordial power spectrum $P_\zeta(k)$ and the scale-dependent non-gaussianities arising on models with non-constant sound speed, applying them to our particular case. Section 4.1 contains the description of the method and of the cosmological data sets. In Section 4.2, we present our results, including the derived limits on the standard inflationary parameters. Finally, we draw our conclusions in Section 5.

## 2. Phenomenological approach to inflation

An alternative approach to describe the inflationary paradigm can be provided by a phenomenological parameterization based on a hydrodynamical picture, through an equations of state [47–49]. During inflation, the equation of state is $p \simeq -\rho \simeq -3H^2 M_{\rm Pl}^2$, while $p \ll \rho$ towards its ending. Here $p$ and $\rho$ are the pressure and the energy density respectively, $H$ is the Hubble parameter and $M_{\rm Pl}$ the reduced Planck mass.[3] With this scenario in mind, one can thus write a parameterization of the equation of state in terms of the number of *e*-folds left to the end of inflation, $|{\rm d}N| \equiv H {\rm d}t$, as

$$\frac{p}{\rho} + 1 = \frac{\beta}{(N+1)^\alpha}. \tag{1}$$

Here the parameters $\alpha$ and $\beta$ are both positive and of order unity. As shown in Refs. [47,48] the parameterization above captures different inflationary models which vastly differ in their observational signatures. This hydrodynamical characterization of the inflationary scenario allows as well for a non-standard, time-varying $c_s$. The sound speed is parameterized via [47]

$$c_s = \frac{\gamma}{(N+1)^\delta}\,, \tag{2}$$

where $\delta \geq 0$, because the sound speed is assumed to grow towards the end of inflation, and $\gamma$ is an arbitrary positive number. The expressions for the derived quantities, as the tensor-to-scalar ratio, the primordial spectral index and its running read as [48]:

$$\begin{aligned} r &= \tfrac{24\beta\gamma}{(N_\star+1)^{\alpha+\delta}}, \\ n_s &= 1 - \frac{3\beta}{(N_\star+1)^\alpha} - \frac{\alpha+\delta}{N_\star+1}, \\ \alpha_s &= -\frac{3\alpha\beta}{(1+N_\star)^{\alpha+1}} - \frac{\alpha+\delta}{(N_\star+1)^2}, \end{aligned} \tag{3}$$

where $N_\star$ indicates the number of remaining *e*-folds at horizon crossing. Notice that both the running $\alpha_s$ and the tilt, $n_s - 1$, are always negative.

## 3. Features in $P_\zeta(k)$ and $f_{\rm NL}$

It has been shown that a consequence of the inflationary models with a varying sound speed of the primordial perturbations is the presence of features in the primordial power spectrum $P_\zeta(k)$ and in the primordial bispectrum $B_\zeta(k)$ [19,50–53,20]. The deviations of the primordial power spectrum from the standard case can be studied by isolating the contributions due to a non-standard $c_s$ as $P_\zeta(k) = P_0(k) + \Delta P_\zeta(k)$. Here $P_0(k) = H^2/(8\pi^2\epsilon M_{\rm Pl}^2)$ is the usual featureless primordial power spectrum. The corrections to the primordial power spectrum generated by the sound speed variations through time are given by [19]

$$\frac{\Delta P_\zeta}{P_0}(k) = k\int_{-\infty}^{0} u(\tau)\sin(2k\tau)d\tau\,, \tag{4}$$

where $u(\tau) \equiv 1 - c_s^{-2}(\tau)$ and $\tau$ is the conformal time. Eq. (4) is valid if the reduction in the sound speed is small, *i.e.* in the $|u(\tau)| \ll 1$ regime [19].

Using ${\rm d}N = -{\rm d}\tau/\tau$, which is valid for a de-Sitter space–time with constant expansion rate, we can write Eq. (2) in terms of the conformal time $\tau$, and therefore the corrections to the primordial power spectrum can be computed as

$$\frac{\Delta P_\zeta}{P_0}(k) = k\int_{\tau_0 e^{N_{\rm i}}}^{\tau_0 e^{N_{\rm e}}} \left\{1 - \gamma^{-2}\left[1 + \ln\left(\frac{\tau}{\tau_0}\right)\right]^{2\delta}\right\}\sin(2k\tau){\rm d}\tau\,, \tag{5}$$

where $N_{\rm e}$ and $N_{\rm i}$ refer to the end and the beginning of the inflationary period, which, in this parameterization (see Eq. (2)), are identified with $N = 0$ and $N \simeq 60$, respectively. In the following, we will fix the number of inflationary *e*-folds to 60.

Fig. 1, top left panel, shows the galaxy power spectrum $P(k)$ at a redshift $z = 0.57$, which corresponds to the mean redshift of the DR9 CMASS sample of galaxies [54]. These power spectrum measurements will be exploited in the next section in their Baryon Acoustic Oscillation (BAO) form to set constraints on the phenomenological inflationary approach studied here. Together with these measurements we show, in the top panel, the galaxy power spectrum for the best-fit $\Lambda$ CDM parameters for the standard inflationary parameterization with $c_s = 1$ [55], together with the galaxy power spectrum for a time-varying $c_s(\tau)$ scenario, fixing $\gamma = 1$ and $\delta = 0.032$.[4] The non-linear galaxy power spectrum in the canonical ($c_s = 1$) $\Lambda$ CDM scheme corresponds to the prediction from the Coyote emulator of Kwan et al. (2015) [56]. The bottom left panel of Fig. 1 illustrates the deviations with respect to the pure-linear case with $c_s = 1$. Notice, from the bottom panel, the oscillatory behaviour imprinted in the galaxy power spectrum, whose amplitude is governed by the parameter $\delta$.

Fig. 1 (top right panel) shows the Planck 2015 temperature anisotropies (TT) data [57], together with the theoretical predictions using the best-fit spectrum in a standard $\Lambda$ CDM cosmology [55] (*i.e.* with $c_s = 1$, see the black curve) and those obtained

[2] Features in the primordial power spectrum may also arise in inflationary models with a sharp step/feature in the inflaton potential [21,22] (see also Refs. [23–38]), or in axion monodromy scenarios [39–45], (see also the recent work of Ref. [46]).

[3] As usual, $M_{\rm pl} = 1/\sqrt{8\pi G_N} \simeq 2.43 \times 10^{18}$ GeV.

[4] This value of $\delta$ corresponds to the upper prior considered here for this parameter, see the following section.