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Cosmic microwave background power asymmetry from primordial sound speed parameter

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The hemispherical power asymmetry in the cosmic microwave background can be explained by the modulation of some primordial cosmological parameters, such as the sound speed of the inflaton. Inspired by new physics beyond the standard knowledge of particle cosmology, this sound speed modulation greatly enriches the cosmological perturbation theory. We numerically examine the mechanism of the sound speed modulation and show it can be nicely consistent with current observations. Furthermore, this mechanism predicts that power asymmetry also exists in the temperature-polarization correlation and polarization autocorrelation of the cosmic microwave background with the same shape and in primordial non-Gaussianity of equilateral type with a particular shape. Therefore, our mechanism is observationally detectable in the forthcoming experiments.

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I. INTRODUCTION

The recently released Planck data reported a hemispherical power asymmetry in the cosmic microwave background (CMB) fluctuations [1] and provided an independent measurement on this anomaly, which was also earlier reported in the Wilkinson microwave anisotropy probe data. Such a power asymmetry can be modeled as a dipolar modulation of a statistically isotropic CMB sky in terms of temperature fluctuations in direction $\hat{n}$ [1]:

$$\frac{\Delta T}{T}(\hat{n}) = s(\hat{n})[1 + A\hat{n}\cdot\hat{p}], \tag{1}$$

where $s(\hat{n})$ is a statistically isotropic map, A characterizes the amplitude of dipolar asymmetry, and $\hat{p}$ is its direction. To translate to the expression of the primordial power spectrum, the modulation required to explain this asymmetry can be written as a spatially varying power spectrum [2],

$$P(k,\vec{r}) = P(k)[1 + 2A\hat{p}\cdot\vec{r}/r_{\rm ls}], \tag{2}$$

where $r_{\rm ls}$ is the distance to the last scattering surface.

The best-fit dipolar asymmetry has an anisotropy direction $(227, -27)$, and the corresponding amplitude is given by $A = 0.072 \pm 0.022$ for the CMB power with $l \lesssim 64$ (and thus $k \lesssim 0.035\ \mathrm{Mpc}^{-1}$) [1]. However, the asymmetry does not necessarily exist at smaller length scales. Particularly, the constraint from the Sloan Digital Sky Survey quasar sample [3] requires $A < 0.0153$ (99% C.L.) for the power asymmetry oriented in the direction of the CMB dipole in which the typical wave number is $k \sim 1\ \mathrm{Mpc}^{-1}$. Thus, any model that accounts for the CMB power asymmetry has to produce a strong scale dependence so that it can be in agreement with both the CMB and the quasar constraints.

As pointed out in [4], a single-field slow-roll inflation model cannot generate such an asymmetry without violating the constraints of the homogeneity of the Universe. The same paper also proposed a so-called Erickcek-Kamionkowski-Carroll (EKC) mechanism based on a curvaton model [5,6] and thus can explain this anomaly without violating the homogeneity constraint. However, the original model is inconsistent with the quasar bound since the signature is scale independent. Also, the model leads to a large value of the non-Gaussianity parameter, which has been ruled out by Planck [7]. Instead, an improved curvaton model in which the curvaton decay takes place after dark matter freezes out was studied [8]. In the presence of super-Hubble isocurvature fluctuations, the power asymmetry can be obtained because of the difference between the value of the curvaton field on one side of the last scattering surface and its average value in the observable Universe. Accompanied by this anomaly, the model predicts an isocurvature contribution to primordial perturbations that may need a fine-tuning on the model's parameters in order to be consistent with the Planck data. However, the violation of the slow-roll condition before inflation can leave an initial spatial gradient for the inflaton and thus may explain the power asymmetry [9]. Moreover, the non-Gaussianities of primordial perturbations may give rise to such a power asymmetry if the squeezed limit of the bispectrum is sufficiently divergent [10].

It was exquisitely observed in [2] that the power asymmetry may arise from a modulation of any cosmological parameters that affect the CMB power spectrum, and a comprehensive analysis was performed that includes isocurvature perturbations, gravitational waves, a variation of the spectral index, a dipolar modulation of the reionization optical depth, and a compensated baryon density. If the value of one cosmological parameter on one side of the CMB sky is different from the one on the other side and the power spectrum is correlated with this parameter, then the power spectrum on one side may differ from that on the other side as well.

Despite the above models, we suggest that the power asymmetry may be explained by a modulation of the sound speed parameter c_s of primordial inflationary perturbations. In general, an inflation model can be realized by a K-essence field minimally coupled to Einstein gravity [11], with the Lagrangian in the form of $P(X,\phi)$ and $X \equiv -g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi/2$. This model may come from some stringy-theory motivation such as an effective description of D-brane dynamics [12] or from the effective single-field description of a coupled multifield system where the heavy modes are integrated out [13]. For the time being, let us put aside its theoretical origin and focus on the phenomenological implication on CMB.

For this type of model, the gradient stability of the inflaton fluctuation is characterized by the sound speed, the square of which is defined as $c_s^2 \equiv P_{,X}/(P_{,X}+2XP_{,XX})$. The subscript "$_{,X}$" denotes the derivative with respect to X. To deal with such inflationary dynamics, it is convenient to introduce the following slow-roll parameters: $\epsilon = -\dot{H}/H^2$, $\eta = \dot{\epsilon}/H\epsilon$, and $s = \dot{c}_s/Hc_s$, where H is the Hubble parameter defined as $\dot{a}/a$. The amplitude of the field fluctuation during inflation is determined by the Hubble rate through $\delta\phi \simeq H/2\pi$, but the freeze-out moment depends on when the perturbation mode exits the sound horizon $k^{-1} \simeq c_s/H$. Therefore, the amplitude of the primordial power spectrum is given by

$$P_\zeta = \frac{P_{\zeta,0}}{c_s}, \qquad P_{\zeta,0} = \frac{H^2}{8\pi^2 M_p^2 \epsilon}, \tag{3}$$

where we introduce $P_{\zeta,0}$, which has an identical form to the power spectrum of a canonical inflation model. Intuitively, a power asymmetry can be obtained if the value of c_s on one side of the CMB sky differs from the one on the other side. To explain this power asymmetry, we may introduce a spatially varying sound speed as follows,

$$c_s(k,\vec{r}) = \bar{c}_s(k)[1 + 2A\hat{p}\cdot\vec{r}/r_{\rm ls}]^{-1}, \tag{4}$$

where $\bar{c}_s$ is the direction-independent part of the sound speed for inflationary perturbations in our observed Universe, and it generally depends on the wave number k.

Now we use the model of multispeed inflation [14] to illustrate the possibility of this sound speed modulation. We phenomenologically consider a double-field inflation model, with one field being described by a dirac-born-infeld-like (DBI) action and the other by a canonical field. The total action is constructed by the sum of the two. Therefore, we take the Lagrangian density of the two fields as

$$\mathcal{L} = \frac{1}{f(\phi,\chi)}(1-\sqrt{1+f\partial_\mu\phi\partial^\mu\phi}) - \frac{1}{2}\partial_\mu\chi\partial^\mu\chi - V(\phi,\chi). \tag{5}$$

Here, ϕ plays the role of the inflaton field and χ is an entropy field, which does not contribute to the background evolution. The DBI-type kinetic term for ϕ involves a coefficient f. This coefficient is often interpreted as a warping factor from the point of view of string cosmology, but right now let us assume it is a function of ϕ and χ for phenomenological consideration. The first interesting property is that these two fields carry different values of the sound speed parameters. For χ, $c_s^\chi = 1$ since its kinetic term is canonical; however, for the inflaton, the sound speed takes the form of

$$c_s(t) = \sqrt{1 - f(\phi,\chi)\dot{\phi}^2}. \tag{6}$$

This model was extensively studied in [15] and was expected to produce a large value of primordial equilateral non-Gaussianity [16] due to the following relation [17],

$$f_{\rm NL}^{\rm DBI} = -\frac{35}{108}\left(\frac{1}{c_s^2} - 1\right). \tag{7}$$

Unfortunately, the interest in such a model ended after Planck since no evidence was found to prove the existence of primordial non-Gaussianities. However, we show that this model may be applied to explain the hemispherical asymmetry if the value of the sound speed varies from one side of the sky to the other.

From (6), the sound speed can be modulated by the field fluctuation $\Delta\chi$. In particular, due to the Grishchuk-Zel'dovich (GZ) effect [18], the $\Delta\chi$ modes at very large scales could bring an enhancement within the observable Universe, which is expected as an approximately linear function of position. In [19], this effect was considered to explain the dipolar anomaly through a curvaton mechanism where the primordial fluctuation of χ has to be responsible for curvature perturbation as well. Thus, the enhancement factor has to be finely tuned to generate the required asymmetry, while the CMB quadrupole is still small enough to accommodate observation. In our case, it is not necessary that the field fluctuation $\delta\chi$ be responsible for the curvature perturbation. Thus, we do not need to require a manifest enhancement on very large scales. Instead, the asymmetry can arise from the so-called warping factor $f(\phi,\chi)$.

By expanding (6) to linear order, one easily derives

$$c_s = \bar{c}_s(t(k))\left[1 + \frac{54}{35}f_{\rm NL}^{\rm DBI}\frac{f_{,\chi}}{f}\Delta\chi\right], \tag{8}$$

where relation (7) was applied. Note that $\bar{c}_s$ slowly varies as a function of the cosmic time during inflation and thus becomes k dependent for perturbation modes at Hubble exit. According to the GZ effect, one expects the field fluctuation to be [19]

$$\Delta\chi \simeq E P_{\delta\chi}^{\frac{1}{2}} \hat{p} \cdot \vec{r}/r_{\rm ls}, \tag{9}$$

at very large scales. During inflation, there is always an approximate relation $P_{\delta\chi}^{\frac{1}{2}} = H/2\pi$ at the moment of Hubble exit. The coefficient E is viewed as an enhancement factor of the GZ effect, and it is found to be tightly constrained by observations if both the asymmetry and power spectrum are generated by the same field as has been analyzed in [19]. There is, however, no reason to require the existence of a very large value of E. Thus, in the following we simply take $E \sim O(1)$ which easily satisfies the bounds provided in [19].

Inserting the field fluctuation (9) into the linearized expansion of the sound speed (8) and comparing with the expected form (4), we get

$$|A(k)| \simeq \frac{27}{70\pi} E(k) H(k) |f_{\rm NL}^{\rm DBI}(k)| \left| \frac{f_{,\chi}}{f}(t_k) \right|, \tag{10}$$

where the amplitude of the hemispheric asymmetry is a function of the comoving wave number. Namely, the coefficients E, H, and $f_{\rm NL}^{\rm DBI}$ at Hubble exit can be k dependent, although such a dependence is negligible in the usual inflation models. Moreover, the k dependence also comes from the evolution of the χ field during inflation, because when the primordial perturbation modes exit the Hubble radius at different times the corresponding value of the χ field is different. This remarkable feature could provide a physical explanation for the observational fact that the power asymmetry is only significant on the cosmological scale but becomes small at the Mpc scale.

Specifically, we consider an example of power-law function, i.e., $f(\chi) \sim \chi^p$. Then, using (3) and (7) we obtain

$$|A(k)| \lesssim \frac{27\sqrt{|1-n_s|}}{35\sqrt{2}} \frac{E P_\zeta^{\frac{1}{2}} |f_{\rm NL}^{\rm DBI}|}{(1 - \frac{108}{35} f_{\rm NL}^{\rm DBI})^{\frac{1}{4}}} \frac{|p| M_p}{\chi(t_k)}, \tag{11}$$

where the bound on the slow-roll parameter from the spectral tilt has been applied. According to the Planck data [7,20], we learn that $n_s = 0.9603 \pm 0.0073$ at 1σ and $\bar{c}_s \geq 0.07$ at 2σ, and the best-fit value of the power spectrum gives $P_\zeta = 22.1536 \times 10^{-10}$. Substituting these values into the inequality yields an upper bound, $|A(k)| \lesssim 8.908 \times 10^{-5} \chi(t_k)^{-1} |pE| M_p$. Typically, we have $|p| \sim O(1)$. Moreover, the constraint on the CMB quadrupole does not favor a manifest enhancement on the amplitude of field fluctuation at very large scales, and thus, we may typically assume $E \sim O(1)$ as well. Eventually, we can use the value of the χ field to generate the required power asymmetry. Namely, for the perturbation mode with $k_a \sim 0.035\ {\rm Mpc}^{-1}$ exiting the Hubble radius, we expect

$$\chi(t_{k_a}) \gtrsim 0.00124 |pE| M_p; \tag{12}$$

when the perturbation mode with $k_b \sim 1\ {\rm Mpc}^{-1}$ exits the Hubble radius, we then need

$$\chi(t_{k_b}) \gtrsim 0.00582 |pE| M_p. \tag{13}$$

Then, the desired asymmetry can accommodate both the CMB and the quasar observations. Such a result suggests that the vacuum of the χ field has to be away from the origin and χ evolves from a small value to a large one during inflation. Phenomenologically, this is easily achieved in a small field model.

Note that, the modulation of the sound speed may lead to potentially dangerous backreaction on the friction term $(3H\dot{\phi})$ of the background dynamics. It is necessary to estimate the amplitude of this contribution. Within our mechanism, the modulation of the sound speed of interest is given by Eq. (8), i.e., $\Delta c_s \sim c_s f_{\rm NL}^{\rm DBI} \frac{f_{,\chi}}{f} \Delta\chi$. To substitute a group of canonical parameter values as provided above, we can easily read that a modulation with $\Delta c_s \lesssim O(10^{-3})$ is enough to explain the power asymmetry in the CMB. Considering that this modulation is achieved within an interval of one Hubble time $\Delta t_H \sim 1/H$, its effect in the friction term is of the order $O(10^{-2})H$, which is much less than the background parameter $3H$. Therefore, the sound speed variation, which is expected to explain the CMB anomaly, does not affect the background inflationary dynamics [21].

II. NUMERICAL ESTIMATE

Following the previous model, the power asymmetry may arise from a modulation of the sound speed that affects the CMB power spectrum without modifying the inflationary background. Therefore, one expects that the current constraint on inflationary models can be safely satisfied. However, since our model allows the value of c_s on one side of the sky to be different from that on the other side, the corresponding CMB power spectrum can be different on the two sides. Specifically, we would like to map the modulation of c_s into the $\Delta C_l^{\rm TT}$ through the relation $\Delta C_l^{\rm TT} = \frac{\partial C_l^{\rm TT}}{\partial c_s} \Delta c_s$. The CMB power spectrum is calculated by $C_l^{\rm TT} = \int P_\zeta(k) \Delta_l^{T2}(k) \frac{dk}{k}$, where $\Delta_l^{\rm T}(k)$ is the transfer function, and it is independent of the primordial power spectrum $P_\zeta(k)$. We assume that the sound speed can be written in the form of $c_s(k, \vec{r}) = \tilde{c}_s(1 + D(k/k_0, \vec{r}))$, where $\tilde{c}_s$ is constant, $D(k/k_0, \vec{r})$ is the small correction term, and $k_0 = 0.74 \times 10^{-4}\ {\rm Mpc}^{-1}$ is the chosen pivot wave number. Employing the relation in Eq. (3), we arrive at $\Delta C_l^{\rm TT}/C_l^{\rm TT} \simeq -D(l, \vec{r})$, where we have used the fact that the transfer function is sharply peaked at value $l \simeq k/k_0$, which is a reflection of the fact that metric fluctuations at a particular linear scale k^{-1} lead to CMB anisotropies predominantly at angular scales $\theta \sim kd$ (where d is the distance to the surface of last scattering).

In order to estimate the effect, we ignore the dependence on $\vec{r}$ and assume a power-law form for the function

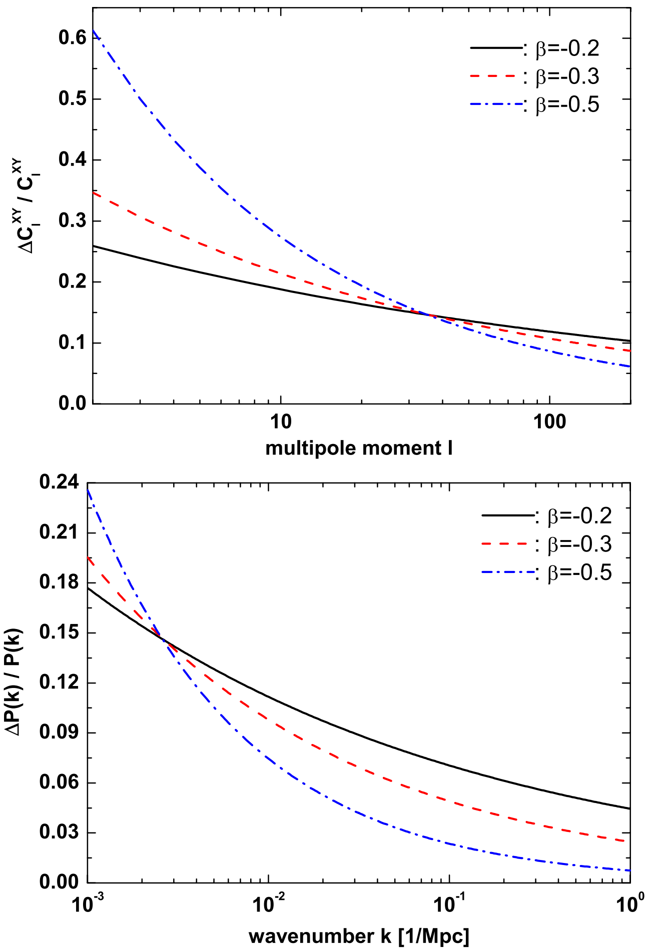

FIG. 1 (color online). The fractional changes $\Delta C_l^{\mathrm{XY}}/C_l^{\mathrm{XY}}$ (XY=TT,TE,EE) in the CMB power spectra (upper) and the fractional change $\Delta P(k)/P(k)$ in the matter power spectrum (lower) for models with different β in our mechanism. Each curve is normalized so that $A = 0.072$.

$D(x) = \alpha x^{\beta}$, where the index $\beta < 0$, since we expect that the anisotropy effect is obvious only at large scales. Following [2], the amplitude parameter α can be fixed by the asymmetry parameter $A = 0.072$, which is determined from the data weighting in all spherical harmonic modes equally up to $l_{\max} = 64$, i.e., $A = \frac{1}{2N}\sum_{l=2}^{l_{\max}}(2l+1)\frac{\Delta C_l^{\mathrm{TT}}}{C_l^{\mathrm{TT}}}$, with $N = \sum_{l=2}^{l_{\max}}(2l+1)$. In the upper panel of Fig. 1, we show the fractional power-spectrum differences, where the cases with $\beta = -0.2, -0.3, -0.5$ are considered. The corresponding fractional change $\Delta P(k)$ in the matter power spectrum induced by the modulations in different cases is presented in the lower panel of the same figure. As expected, we find that these modified the CMB power and matter power spectra only on small scales.

III. PREDICTION

In addition to the temperature autocorrelation, there are also temperature-polarization correlations (C_l^{TE}) and polarization autocorrelations (C_l^{EE}). By a similar analysis as above, we find that in this model, the fractional changes $\Delta C_l^{\mathrm{TE}}/C_l^{\mathrm{TE}}$ and $\Delta C_l^{\mathrm{EE}}/C_l^{\mathrm{EE}}$ should be exactly the same as those of $\Delta C_l^{\mathrm{TT}}/C_l^{\mathrm{TT}}$, which provides an excellent opportunity to test this model with the polarization observations.

Another interesting prediction of this model is related to the primordial non-Gaussianity parameter of equilateral type, which takes $f_{\mathrm{NL}}^{\mathrm{eq}} \simeq -\frac{1}{3}(c_s^{-2} - 1)$. It is expected that a large value of primordial non-Gaussianities may be generated by this model if one tunes c_s to be a small quantity such as in the model of DBI inflation, and thus the corresponding model is now strongly constrained by the Planck data. However, if we expect that there exists a modulation of sound speed which accounts for the power asymmetry, then we also reach an interesting conclusion that the power of the bispectrum is asymmetric as well. In particular, in this model the value of $f_{\mathrm{NL}}^{\mathrm{eq}}$ is scale dependent, and also at large scales, the asymmetry of $f_{\mathrm{NL}}^{\mathrm{eq}}$ should be significant. This signature, together with the signature of polarization modes, can be tested by future observations.

IV. CONCLUSION

Until now, it is still unknown whether a hemispherical asymmetry in the CMB fluctuations is associated with the background of observational data or indicates nontrivial physics beyond the standard scenario. While staying aware of the foreground contamination of data, we need to question plausible physical explanations for generating such an asymmetry. After the Planck Collaboration reported this anomaly in the data release, a few papers appeared which attempted to provide a physical mechanism; namely see [2,19,22].

In this paper, we explore another mechanism of generating the hemispherical asymmetry in the CMB fluctuations by requiring a statistically inhomogeneous sound speed parameter. It is well known that the sound speed parameter is the key factor to govern the propagations of fluctuations in any dynamical system. This outstanding property is widely studied in particle physics, thermodynamics, and condensed matter physics. It has also been well studied in cosmological perturbation theory at late stages such as in the formation of the large scale structure. Based on this general argument, we are motivated to look for observational signals of the primordial sound speed. To illustrate the feasibility of our mechanism, we phenomenologically consider a model of multispeed inflation, which involves two scalar fields. One of them is assumed not to contribute to the inflationary background at all. However, it couples to the kinetic term of the inflaton field, and its fluctuation can modulate the inflaton's sound speed. After that, the EKC mechanism can easily yield a potentially statistical anisotropy on the power spectrum. By performing a numerical estimate, we show that the model can generate the power asymmetry in agreement with both the CMB observation and the quasar constraint.

Furthermore, the model gives promising predictions on the polarization correlations and bispectrum, and thus, observations of CMB polarization and the large scale structure will significantly improve the constraints on this anomaly.

It is important to note that, although the model under consideration is nonconventional in the knowledge of effective field theory in particle physics, the underlying theory leading to this DBI-type Lagrangian is expected to be more fundamental, for instance, the stringy background. Thus, the corresponding mechanism, if detectable, provides a potential window to explore the new fundamental physics in today's and in forthcoming cosmological experiments. Although it is still too far to make any conclusive evidence, our study can be viewed as a meaningful attempt in this field.

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