Physics Letters B 739 (2014) 285–292

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Standard Clock in primordial density perturbations and cosmic microwave background

Xingang Chen [a,*], Mohammad Hossein Namjoo [b,*]

[a] Department of Physics, The University of Texas at Dallas, Richardson, TX 75083, USA
[b] School of Astronomy, Institute for Research in Fundamental Sciences (IPM), P.O. Box 19395-5531, Tehran, Iran

ARTICLE INFO

Article history:
Received 9 June 2014
Received in revised form 26 September 2014
Accepted 2 November 2014
Available online 5 November 2014
Editor: S. Dodelson

ABSTRACT

Standard Clocks in the primordial epoch leave a special type of features in the primordial perturbations, which can be used to directly measure the scale factor of the primordial universe as a function of time $a(t)$, thus discriminating between inflation and alternatives. We have started to search for such signals in the Planck 2013 data using the key predictions of the Standard Clock. In this Letter, we summarize the key predictions of the Standard Clock and present an interesting candidate example in Planck 2013 data. Motivated by this candidate, we construct and compute full Standard Clock models and use the more complete prediction to make more extensive comparison with data. Although this candidate is not yet statistically significant, we use it to illustrate how Standard Clocks appear in Cosmic Microwave Background (CMB) and how they can be further tested by future data. We also use it to motivate more detailed theoretical model building.

1. Introduction

Our understanding on the origin of the Universe has advanced considerably in recent years through interactions between experiments and theories. We have a large number and variety of ongoing and upcoming experiments that are mapping the entire observable universe. One of the most important achievements of these experiments is to produce, one way or the other, different and complimentary maps of the distributions of large scale structures, including various spectra and objects, in our Universe. These maps are the gold mines to advance our knowledge in cosmology. All these large scale structures originated from some tiny fluctuations in the very early universe, the primordial perturbations. One of the most beautiful ideas in modern cosmology is that these perturbations are seeded by quantum fluctuations of fields present in an early epoch responsible for the Big Bang. By studying properties of these maps, we learn properties of this epoch, as well as fundamental physics in conditions that are inaccessible for experiments on Earth.

In the past two decades, the data from CMB and Large Scale Structures (LSS) strongly support the inflationary paradigm [1–5] as the leading candidate for this primordial epoch. The simplest inflationary models predict the primordial perturbations to be superhorizon, approximately scale-invariant, adiabatic and Gaussian [6–10]. All of these have been verified to some extent by the results from the Wilkinson Microwave Anisotropy Probe (WMAP) [11] and the Planck satellite [12,13]. The properties of these perturbations are summarized quantitatively by two of the six parameters in the Standard Model of Cosmology, the ΛCDM model.

On the other hand, other possibilities have also been speculated as alternative theories to the inflationary scenario. From the perspective of theoretical model building, none of them has been as successful as inflation. See Refs. [15–18] for the current status. Nonetheless, models may be improved or become complicated to fit the data. This is possible because there are only two parameters in the Standard Model that are relevant to the primordial epoch, leaving rooms for theoretical freedoms. Therefore an equally important approach in cosmology is to search for beyond-Standard-Model signals in data that can be used to distinguish different scenarios.

Phenomenologically one can distinguish four different kinds of primordial epochs, classified by the time dependence of the scale factor $a(t) \sim t^p$: the fast-expanding or fast-contracting scenarios, and the slowly-expanding or slowly-contracting scenarios. (The contracting scenarios require a bounce to match the Big Bang.) Each of them has a different fingerprint index in terms of the parameter p [19,20]. The acceleratedly-expanding scenario, namely

* Corresponding authors.
E-mail addresses: Xingang.Chen@utdallas.edu (X. Chen), MohammadHossein.Namjoo@utdallas.edu (M.H. Namjoo).

http://dx.doi.org/10.1016/j.physletb.2014.11.002
0370-2693/

inflation, has $|p| > 1$; the fast-contracting scenario [21,22] has $p \sim \mathcal{O}(1) < 1$; the slowly-expanding scenario has $-1 \ll p < 0$; and the slowly-contracting scenario [23] has $0 < p \ll 1$.[1] For $p > 1$, t runs from 0 to $+\infty$; for all other p, t runs from $-\infty$ to 0. The choices of t are based on the requirement that the quantum fluctuations in this epoch exit the horizon, so that they can give rise to the acoustic oscillations in the CMB after reentry during the Big Bang.

The primordial perturbations, which are seeded by quantum fluctuations in these epochs, consist of scalar and tensor modes. While the scalar mode determines the density perturbations at the beginning of the Big Bang as the source of the large scale structures, the tensor mode corresponds to the gravitational quantum fluctuations and records the magnitude of the Hubble parameter during the epoch. Therefore the tensor mode serves as a good discriminator between the scenarios with fast-evolving scale factor and those with slowly-evolving scale factor. In particular, if the tensor mode origin of the recent CMB B-mode detection by the BICEP2 experiment [14] is confirmed, both the slowly-expanding and slowly-contracting scenarios will be ruled out. Nonetheless, phenomenologically, the tensor mode does not distinguish the inflation from the fast-contracting scenarios. For example, both the inflation and the matter contraction can give rise to observable tensor mode with approximately scale-invariant spectra [21,22].

In this Letter, we consider a different type of observables. A main reason the degeneracy of scenarios could exist is that the observables we mentioned so far (namely the approximately scale-invariant scalar and tensor modes) are all convoluted consequences of the scale factor $a(t)$, the defining property of different scenarios. A direct measurement of $a(t)$ would provide an independent and direct evidence for a scenario, as was done for the late-time accelerated universe using the Standard Candles [24,25]. This turns out to be possible: oscillating massive fields in the primordial epoch can serve for this purpose as the Standard Clocks [19,20,26]. The massive field oscillates with a frequency that can be thought of as ticks of a clock. This Standard Clock imprints its ticks as a special type of features in the primordial perturbations, thereby letting some imprints in the CMB angular power spectra, the non-Gaussianities and the distribution of large scale structures. The patterns of these ticks are a direct record of $a(t)$ of the primordial universe.

In this Letter, after summarizing the main results of the theoretical proposal of the Standard Clock, we compare its key predictions with the Planck 2013 residual data. A full-scale comparison will be the subject of the next paper [27]. Here we focus on one interesting candidate emerging from this comparison, although it is still not statistically significant. Motivated by this candidate we construct explicit Standard Clock models and compute the full power spectrum. This is a completion of the above key predictions, under the same number of model parameters. We again see encouraging signs after this prediction is compared with the Planck data.

2. Standard Clocks

We start with a summary of the key requirements and properties of the Standard Clock [19,20,26]. There are two requirements to have a Standard Clock in a primordial scenario:

1. We need an extra massive field with mass much larger than the event-horizon mass-scale of the corresponding primordial epoch. For example, for inflation this mass scale is the Hubble parameter. This massive field is excited classically by some sharp features and oscillating.
2. This massive field starts to oscillate at least several efolds after the beginning of the *observable* primordial epoch. For example, for inflationary scenario, the observable scales include approximately 60-efolds towards the end of inflation; the massive field has to *start* oscillating at least a few efolds within the 60-efolds, but not at or before the beginning of these 60-efolds.

Standard Clocks generate two qualitatively different types of signals in the primordial perturbations, which are connected to each other and contain different properties. It is important to classify them and sort out which properties can be most robustly used to measure $a(t)$, which are less robust but can be auxiliary, and which cannot [19,20].

The first type of signal is generated by the sharp feature that excites the massive field. Like all sharp feature signals, this signal has a characteristic sinusoidal running as a function of scales,

$$\sim \cos(K/k_0 + \text{phase}), \tag{2.1}$$

where k_0 is both the K-location of the sharp feature and the wavelength of the oscillation. Here $K \equiv k_1 + k_2 = 2k_1$ for power spectrum, $K \equiv k_1 + k_2 + k_3$ for bispectrum and so on. In inflation models, examples of various sharp features have been studied in e.g. Refs. [28–33]. But we emphasize that the statement here is stronger – this leading order behavior also applies to non-inflationary scenarios [19,20]. The sinusoidal running itself cannot be used to measure $a(t)$ because it is qualitatively the same for all scenarios. This can be intuitively understood – the sharp feature has only one click and it does not contain any clock information.

The second type of signal is generated by the oscillation of massive field after it is excited. The most important property of this signal is its characteristic resonant running, which we shall explain more with explicit examples shortly. The pattern between successive oscillations is determined by the ticks generated by the Standard Clock and the scale factor $a(t)$, which is unique for each scenario.

Overall, in the *full* Standard Clock signals, the following are the two most robust properties that can be used to distinguish different scenarios.

A. *The clock signal.* The fingerprint resonant running signal generated by the Standard Clock, as a fractional correction to the leading order approximately scale-invariant power spectrum, $\Delta P_\zeta / P_{\zeta 0}$, or as the leading order non-Gaussianities, is given by

$$C\left(\frac{K}{k_r}\right)^{\alpha} \sin\left[\frac{p^2}{1-p}\omega\left(\frac{K}{k_r}\right)^{1/p} + \varphi\right]. \tag{2.2}$$

This profile contains the fingerprint of different scenarios, specified by the index p. K is as defined above; ω is the frequency of the background oscillation induced by the Standard Clock in unit of the Hubble parameter H_0 (H_0 is evaluated at the time of sharp feature t_0); k_r denotes the first resonant K-mode at t_0; C is the amplitude; φ is a constant phase, whose value depends on different correlation functions and models. For expanding scenarios, $K > k_r$; for contracting scenarios, $K < k_r$. The fingerprint resonant running refers to sin[...], of which the functional form of the argument is simply the inverse function of $a(t)$. By measuring this functional form, we know $a(t)$ directly, so this is the most important part of the clock signal. The envelop behavior specified by the parameter α can be model-dependent even within a scenario,

[1] The case $p \sim \mathcal{O}(-1) > -1$ ($-\infty < t < 0$) is also acceleratedly expanding.