Probing the origin of our universe through primordial gravitational waves by Ali CMB project (Postprint)

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Abstract

This is a research highlight invited by SCIENCE CHINA Physics, Mechanics & Astronomy.

Full Text

Preamble

Probing the Origin of Our Universe Through Primordial Gravitational Waves: The Ali CMB Project

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Introduction

Gravitational waves (GWs), predicted by Einstein in 1916 based on the classical theory of General Relativity (GR), were recently detected by LIGO [**?**]. This breakthrough is expected to initiate a novel probe of cosmology, the nature of gravity, and fundamental physics. In general, GW signals can be classified into two categories: waves from astrophysical sources and waves from cosmological sources. Accordingly, numerous astronomical and cosmological experiments are under design across the world [**?**]. China is playing a particularly important role in this field, having strengthened a series of fundamental scientific subjects—including cosmic evolution, structure of matter, origin of life, and cognitive science—in its 13th National Five-Year Plan [1].

The Ali project, which aims to measure the polarization patterns of the cosmic microwave background (CMB) radiation, was proposed in 2014 under the leadership of Xinmin Zhang's group and has become very promising for exploring primordial GWs.

Primordial Gravitational Waves

Primordial GWs were produced from quantum fluctuations of our universe in the very earliest moments after the Big Bang [**?**]. Since the energy scale of the universe was extremely high during this epoch, the amplitudes of these tensor perturbations could be large enough to affect physics at later times, particularly by leaving specific imprints in the B-mode of CMB polarization. These signals, however, experience redshifting and will damp away within the frequency bands sensitive to astronomical instruments. Only primordial GWs with frequencies below 10^{-15} Hz survive throughout cosmic expansion, as their physical wavelengths are of the order of the observed universe today. Probing these signals requires major efforts devoted to designing cosmological experiments, specifically high-precision measurements of CMB polarization [**?**, **?**, **?**].

Inflationary Cosmology

Inflationary cosmology suggests that the universe underwent a short period of nearly exponential expansion in the very early times, diluting all unwanted primordial relics produced from the Big Bang [**?**]. More importantly, during inflation, the background scalar field responsible for driving inflation gives rise to density fluctuations of quantum origin. Initially, these wavelengths were inside the Hubble radius but were stretched to super-Hubble scales by the exponential expansion of space. These primordial modes subsequently become classical and provide the seeds for the formation of large-scale structure (LSS) and CMB anisotropies [**?**].

In addition to primordial density fluctuations, inflation also produces primordial tensor perturbations—namely, primordial GWs [**?**]. These fluctuations can be described by a traceless and transverse tensor of metric perturbation h_{ij} governed by a generalized Klein-Gordon equation. In Fourier space, each mode h_k denoted by a fixed co-moving wave number k obeys the following equation of motion:

$$h_k'' + 2\frac{a'(\tau)}{a(\tau)}h_k' + k_k^{2h} = 0,$$

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[1] http://www.gov.cn/xinwen/2016-03/17/content_5054992.htm

where the prime denotes the derivative with respect to conformal time τ, and its physical frequency is given by $f = k/(2\pi a)$, with a being the scale factor that characterizes the size of the universe. From this equation, one can see that h_k keeps oscillating when $k > a'/a$, thus consistently connecting with the quantum state of the Bunch-Davies vacuum at the very beginning. During inflationary expansion, h_k gets squeezed on super-Hubble scales where $k < a'/a$. This causal mechanism predicts a nearly scale-invariant power spectrum for primordial GWs.

Two quantities can be used to describe the physics of primordial GWs: the power spectrum P_{gw} at the primordial era and the energy spectrum Ω_{gw} at present. The former depicts the behavior of GWs at very early times, while the latter corresponds to what can be measured in current and future observations. They are related through a transfer function that characterizes the detailed information of cosmological evolution [**?**]. One can also use the tensor-to-scalar ratio r, defined as the ratio of the amplitudes of power spectra for tensor and scalar modes. As an example, we consider an inflation model that yields a primordial GW spectrum with $r = 0.1$. Its energy spectrum and a comparison with various experiments are provided in Figure 1 [Figure 1: see original paper].

Alternative Cosmological Paradigms

Inflationary cosmology, however, is not the unique paradigm for the very early universe. Both the hot Big Bang and inflationary cosmology suffer from an intrinsic conceptual problem: the existence of an initial cosmic singularity. According to the proof by Hawking and Penrose [**?**] and later extended by Borde and Vilenkin [**?**], the universe seems to begin from a spacetime singularity with infinitely large energy density and temperature, at which known physical laws would fail. To address this issue, cosmologists have been forced to search for paradigms of the very early universe beyond inflation, such as bounce cosmology [**?**], cyclic universe [**?**], and emergent universe [**?**, **?**]. Within these scenarios, the Big Bang singularity can be replaced by either a nonsingular bounce due to quintom matter [**?**], non-canonical kinetic operators [**?**], or a quasi-Minkowski spacetime realized by string theory [**?**].

This raises the question of whether these cosmological paradigms can be differentiated by observations. This issue was discussed in [**?**], which pointed out that careful characterization of the power spectrum of primordial B-mode polarization can be used to distinguish between various paradigms of very early universe cosmology. Based on cosmological perturbation theory, one can obtain consistency relations between the spectral index n_t and the tensor-to-scalar ratio r within different models:

- Inflationary cosmology: $n_t = -r/8$ [**?**]
- Nonsingular bounce cosmology involving matter contraction: $n_t \approx 0$ [**?**]
- Emergent universe scenario realized by string-theory thermodynamics: $n_t \approx 1 - n_s$ [**?**]

- Ekpyrotic bounce cosmology: the power spectrum of primordial GWs is predicted to be blue with $n_t \approx 2$ [?]

If a nonsingular bounce occurred before inflation, one can also avoid the initial singularity [?], and the power spectrum of primordial GWs presents an oscillatory and damping feature at large length scales [?, ?]. Therefore, high-precision measurement of primordial GWs becomes crucial for probing the origin of the universe.

Current Constraints and Future Prospects

Thus far, the most representative CMB experiment is the Planck project supported by the European Space Agency, which has measured temperature anisotropies, E-mode polarization, and lensing B-mode at high precision. However, the Planck satellite has not yet observed any primordial B-mode, instead providing only an upper bound of $r < 0.11$ at 2σ confidence level [?]. A joint analysis of data from the BICEP2/Keck Array and Planck can improve this limit to $r < 0.07$ at 2σ [?, ?]. Thus, there remains a promising opportunity to explore the parameter space of primordial GWs [?]. In particular, the Ali international collaboration led by the Institute of High Energy Physics at the Chinese Academy of Sciences will be the first ground-based CMB experiment in the northern hemisphere and is expected to improve the upper bound to the level of 1%.

Scientific Importance of the Ali CMB Project

We conclude by highlighting the scientific importance of the Ali CMB project currently under design. Over the past couple of decades, modern cosmology has achieved numerous successes, yet physicists still do not understand the origin of the universe. The standard paradigm of inflationary Big Bang cosmology can interpret observational data precisely but suffers from the initial singularity problem. Nonsingular cosmology can avert this puzzle. Both inflationary and nonsingular models predict the existence of primordial GWs, but with different patterns. By detecting and measuring these signals in CMB polarization experiments, we have the opportunity to probe the origin of the universe—this is a major goal of the Ali project under design in Tibet, China.

High-precision B-mode measurement will enable us to extract detailed information about primordial GWs, allowing us to differentiate among various scenarios for the very early universe and extending our knowledge to regimes close to quantum gravity—territory that has never before been explored.

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Note: Figure translations are in progress. See original paper for figures.