Transactions on Computer Science and Intelligent Systems Research
ISSN: 2960-1800, eISSN: 2960-2238 | Volume 7
TPCEE 2024

Probing Inflation Through Cosmic Microwave Background (CMB): Current Evidence and Future Prospects

Weixuan Feng

Department of Physics & Atmospheric Science, Dalhousie University, Halifax, Canada

qq550755273@gmail.com

Abstract. The basic concepts of the Big Bang theory and the inflation theory are introduced in this paper. Besides, this paper concludes the current research on modern cosmology, especially for the Big Bang theory and the inflation model. In addition, some current and future Cosmic Microwave Background (CMB) experiments are also summarised. In the final part, some new unsolved problems and interdisciplinary connections in modern cosmology related to the Big Bang theory and the inflation model are mentioned.

Keywords: Cosmology; Cosmic Microwave Background; Big Bang theory; Inflation Model.

1. Introduction

The universe began with an extremely hot and dense singularity, which exploded and let the universe expand and cool until now. Numerous problems about that process confuse physicists. In order to solve the problem, physicists developed the Big Bang theory in the last century. The Big Bang theory has a significant impact on the development of modern cosmology. Namely, the theory provides a theoretical prediction for the evolution and origin of the universe. On the other hand, because of the incomplete Big Bang theory, the inflation theory was developed as complementary to the Big Bang theory; for instance, the inflation theory provides an opportunity to address the horizon problem, the flatness problem, and the monopole problem.

2. Theoretical Foundations of Inflation

2.1. Problems with the Standard Big Bang Model

a. Horizon problem

The horizon problem is related to the Big Bang Model, which is a crucial puzzle in cosmology. Due to the limitation of the speed of light, some regions of the universe should not have causal contact. However, the Horizon problem describes that the universe's matter and temperature distributions are remarkably uniform, which conflicts with the current Big Bang Model.

b. Flatness problem

The current Big Bang Model shows the universe's curvature increasing as time passes. However, the observation results from the Wilkinson Microwave Anisotropy Probe (WMAP) found that the universe's geometry structure is flat [1]. This is the unignorable conflict between the Big Bang theory and observation.

c. Monopole Problem

The monopole problem is an appreciable issue in cosmology. The Grand Unified Theory predicts that large amounts of magnetic monopolies existed in the early universe [2]. However, none have been found in the observable universe or in experiments.

2.2. Inflationary Solution

a. Concept of exponential expansion

The distance between stars and galaxies in the earlier universe was much smaller than today [3]. Therefore, exponential expansion refers to the rapid expansion during the earlier stage of the universe, which is described by the cosmic inflation theory.

b. Key features of inflation: homogeneity and isotropy

The distribution of matter in the universe is uniform on a large scale, which is called homogeneity. Space experienced an exponential expansion in the earlier stage of the universe. The expansion speed is so fast that the matter in the universe becomes uniform [4].

Isotropy is another feature of inflation, which means the observation result is unchanged in all directions of the universe. The inflation provides a possible solution for homogeneity and isotropy [4].

2.3. Predictions of Inflation

a. Generation of primordial density fluctuations

The quantum fluctuations create primordial density fluctuations in the inflation of earlier stages of the universe [5]. The quantum fluctuations were amplified to the universe size during the earlier stage of the universe, which formed the structure of galaxies.

b. Primordial gravitational waves

Most inflationary models predict that primordial gravitational waves were produced by the inflation [6]. The violent expansion during the earlier stage of the universe generated the gravitational wave in spacetime, which is the primordial gravitational wave.

3. The Cosmic Microwave Background (CMB)

3.1. Discovery and Significance

a. Historical context: discovery of the CMB by Penzias and Wilson

The discovery of CMB changed modern cosmology. In 1964, Arno Penzias and Robert Wilson, two scientists who worked at Bell Labs in the US, found an unexpected faint in their new radio telescope. Initially, they were accounted for by the instrument noise. However, they realized the faint was uniform, which means the radiation was coming from all directions in the universe. This is undisputed evidence for cosmological significance.

b. Role of the CMB in confirming the Big Bang theory

The observation of CMB provides multiple evidences for the Big Bang theory. For instance, the black body spectrum, cosmic microwave radiation with a temperature of 2.726 +/- 0.010 K [7], came from the fallout of the beginning of the universe, which can be considered as a solid evidence of Big Bang. Additionally, the existence of a tiny temperature difference in the locate area, known as temperature anisotropies, of the universe shows that the temperature of CMB is not perfectly uniform. The pattern of temperature anisotropies from CMB contains the geometry and composition information of the space structure [8], which helps us establish the Big Bang theory.

3.2. CMB Observations and Experiments

a. Overview of major CMB experiments

Several major CMB experiments have been developed over the past few decades. For instance, the Cosmic Background Explorer (COBE), a satellite from NASA launched in 1989, aimed to study the CMB radiation and provided the evidence for the Big Bang theory. Moreover, the Planck Space Observatory is the latest and most advanced space CMB mission launched by the European Space Agency in 2009. The goal of Planck Space Observatory is to measure the CMB with unprecedented precision and provide scientists with accurate data.

b. Key findings and their relevance to inflation

The key findings of COBE provided strong evidence for the inflation theory. Namely, the FIRAS, an instrument on COBE, made a precise measurement for the blackbody spectrum, which offers firm support for the Big Bang theory [9]. Additionally, COBE was the first detection of intrinsic anisotropy in the CMB and confirmed the existence of primordial density fluctuations in the early universe [7], which is one of the key evidence for inflation theory.

On the other hand, the Planck Space Observatory also provides strong proof for the inflation theory. Specifically, the precise data of CMB temperature and polarization anisotropies from the Planck allow scientists to obtain detailed information of gravitational waves from earlier universes, significantly improving the understanding of inflation and its predictions [10].

4. Current Evidence for inflation from CMB

4.1. Temperature Anisotropies

a. Analysis of the CMB temperature power spectrum

Analyzing the temperature power spectrum of CMB, which included geometry, composition, and the seeds of structure formation [11] provides a statistical study of temperature anisotropies in the earlier universe.

b. Implications for inflationary models

The information about the earlier universe can be inferred by analyzing temperature anisotropies. On the other hand, the temperature anisotropies measurement of the CMB also provides strong evidence for inflationary models and restricts the parameters in the inflationary models [12].

4.2. Polarization Anisotropies

a. E-mode and B-mode polarization

E-mode (gradient component) and B-mode (curl component) are two components of the polarization of CMB. Specifically, the E-mode is produced by the density fluctuations; however, the B-mode is produced both by the gravitational waves and density fluctuations [13]. The different properties between the two models can used to distinguish their origin [14].

b. Detection of B-modes as evidence for primordial gravitational waves

The detection of B-modes is a valid evidence of the primordial gravitational waves. The reason is a unique curl pattern can be observed in the detection of B-mode. Therefore, B-mode can be regarded as the distinctive signature of gravitational waves, which can be used to probe the physical properties of the earlier universe stage [15].

5. Future Prospects in Probing Inflation Through CMB

5.1. Upcoming CMB Experiments

a. Future missions

Cosmic Microwave Background Stage 4 (CMB-S4) is a next-generation experiment about the cosmic microwave background, which is designed to provide complementary data about dark energy and inflation [16]. In addition, LiteBIRD, a space-based mission, will also present a precise result for measuring the polarization of CMB, which complements CMB-S4 [17].

b. Expected improvements in sensitivity and resolution

CMB-S4, an experiment roughly ten times better than current experiments, will provide significantly better results in measuring CMB polarization in the future [18]. Moreover, LiteBIRD offers a 30 arcminute angular resolution of CMB polarization maps, significantly improving pace-based missions [19].

5.2. Technological Advances

a. Advances in detector technology and data analysis techniques

Multi-band Observations, a particular technology used both in CMB-S4 and LiteBIRD, allow the researchers to detect the CMB in multiple different wavelengths, which can separate the CMB signal from the foreground contamination and identify the properties of foregrounds [20].

Furthermore, Large-scale Integration (LSI) is a new data analysis technique that integrates many detector elements onto a single chip.

b. Potential for new discoveries

With the help of CMB-S4, high-precision key cosmological parameters will be found, which will improve our understanding of the fundamental nature of space and time and the evolution of the universe [21]. On the other hand, the LiteBIRD, an upcoming CMB experiment, will be able to find the faint B-mode polarization signal from primordial gravitational waves, thereby helping us understand the earlier stage of the universe [19].

5.3. Theoretical Developments

a. New inflationary models and their testable predictions

Some new inflationary models were developed recently, which could be the new methods to address the limitations of current inflationary models and make more precise predictions for the universe. In particular, warm inflation theory, a variant of cosmic inflation theory, states that the universe will reheat itself during the inflation process instead of after inflation ends [22]. Compared with the traditional inflationary models, warm inflation theory has some unique testable predictions. Specifically, a particular spectral shape of the primordial power spectrum can be predicted by the warm inflation theory. Moreover, the warm inflation theory also predicts potentially detectable levels of non-Gaussianity that could exist in the CMB [23].

On the other hand, string theory inflation, a new type of inflationary model built within the string theory, offers an acceptable explanation of the early universe states and the origin of cosmic inflation [24]. String theory inflation predicts the existence of the QCD axion, a new type of particle that arises from the string theory and could influence the earlier universe [25].

b. Integration with other observational data

The unknown cosmological parameters can be determined, and some new fundamental physical properties of the universe can be found by combining the CMB data with other observational data, such as galaxy surveys and supernova observations [26]. For instance, the Large-Scale Structure Surveys (LSS), an effective method to analyze the distribution of dark energy in the universe, can enhance the understanding of the universe's evolution.

6. Challenges and Open Questions

6.1. Technical and Instrumental Challenges

a. Mitigating foreground contamination

Foreground contamination is radiation interference from celestial objects, such as galaxies and the Milky Way, during the observation of CMB. Moreover, foreground contamination during the observation would significantly affect the detection of faint signals, such as the B-mode polarization [27]. Thus, mitigating foreground contamination plays an essential role in analyzing CMB observation data.

b. Improving detector sensitivity and accuracy

Improving the sensitivity of the detectors and developing advanced data analysis methods during the CMB experiment play a role in mitigating foreground contamination. In particular, superconducting detectors, detectors working in low temperatures with minimal thermal noise, have the capacity to revolute the field of CMB observation. Through this method, the faint signals that were inaccessible in the previous experiment would become available in future observation [28]. On the other hand, advanced component separation, a method for data analysis, is critical for improving detector sensitivity and accuracy. The goal of component separation is to separate the CMB signal from the foreground contamination based on their morphological differences [29], which allows an accurate measurement of the temperature of CMB.

6.2. Theoretical Uncertainties

a. Refining models of inflation

The inflation theory has explained many cosmological observation results. However, there still are numerous theoretical uncertainties in the current model. Namely, the exact properties of the inflation field, a hypothetical scalar field, are still unknown; there are many possible results within the current model of particle physics and string theory [30].

Additionally, the end of inflation, alternatively referred to as graceful exit, is a significant challenge in refining the inflation model [31]. To be more specific, inflation theory shows that inflation needs to end at the right time in order to create the matter and radiation we observe today. However, there are still theoretical uncertainties in achieving this stage of the end of inflation.

b. Understanding the initial conditions

The explanation of the mechanism during the beginning stage of inflation is still unclear, which is related to the initial condition problem. Furthermore, the aim of solving the initial condition problem is to find which condition is necessary for inflation to begin. Solving the initial conditions problem plays a crucial role in comprehending what happened before the inflation began and how the universe became the state that allowed the inflation to start [32].

6.3. Interdisciplinary Connections

a. Connections with particle physics and high-energy theory

The earlier stage of the universe, a high temperature and energy environment, provides a unique laboratory condition for high-energy theory. On the other hand, the development of particle physics offers an opportunity to improve the essential theoretical foundations of inflation models. In detail, cosmic rays are high-energy particles from outer space that carry information from their origin, such as the earlier universe. Cosmic rays provide a unique method to research the properties of dark matter and the early universe [33]. From another perspective, due to the extremely hot and dense environment of the earlier universe, the elementary particles behave differently than today. Therefore, a deeper understanding of particle physics is the key to understanding the earlier universe.

b. Potential implications for fundamental physics

The observation and analysis of CMB is capable of improving our understanding of fundamental physics. The research on the earlier universe offers a new insight into the interaction between elementary particles, which may refine the current framework of fundamental physics. For instance, the Big Bang Nucleosynthesis, a unique event that is difficult to recreate in the current laboratory, in the earlier universe provides a test of the standard model of particle physics [34]. Additionally, due to the limitations of general relativity, such as explaining the physical properties of inside black holes or the very early universe, cosmological observations, such as the detection of CMB and gravitational waves, could provide a unique arena for refining gravity theories and exploring alternative theories of gravity [35].

7. Conclusion

The Big Bang theory provides an opportunity to understand the origin and evolution of the universe. On the other hand, the inflation theory addresses a multitude of problems in the Big Bang theory, such as the horizon problem, the flatness problem, and the monopole problem. In addition, the CMB observations and experiments, such as COBE, offer accurate data for improving the inflation theory, which also provides multiple significant evidence for the inflation theory. Furthermore, the CMB-S4 and LitreBIRD, new types of upcoming CMB experiments, will give physicists a chance to refine the current theory and improve the model of the evolution of the universe. Besides, there are still some instrumental challenges and theoretical uncertainties in observing CMB and the current Big Bang theory and inflation model.

References

[1] National Aeronautics and Space Administration.

[2] Fulvio Melia, A resolution of the monopole problem in the R h = c t Universe.

[3] Modern Cosmology (Scott Dodelson, 2003) P1.

[4] Guth, A. H. (1981). The inflationary universe: A possible solution to the horizon and flatness problems. Physical Review D, 23 (2), 347.

[5] Mukhanov, V. F., & Chibisov, G. V. (1981). Quantum Fluctuations and a Nonsingular Universe. JETP Lett, 33, 532-535.

[6] Rubakov, V. A., Sazhin, M. V., & Veryaskin, A. V. (1982). Graviton creation in the inflationary universe and the grand unification scale. Physics Letters B, 115 (3), 189-192.

[7] Smoot, G. F., et al. (COBE Collaboration). (1992). Structure in the COBE differential microwave radiometer first-year maps. Astrophysical Journal, 396, L1-L5.

[8] Hu, W., & Dodelson, S. (2002). Cosmic microwave background anisotropies. Annual Review of Astronomy and Astrophysics, 40 (1), 171-216.

[9] Boggess, N. W., et al. (1992). The COBE mission: Its design and performance two years after launch. Astrophysical Journal, 397, 420.

[10] Planck Collaboration. (2020). Planck 2018 results. X. Constraints on inflation. Astronomy & Astrophysics, 641, A10.

[11] Hu, W., & Dodelson, S. (2002). Cosmic microwave background anisotropies. Annual Review of Astronomy and Astrophysics, 40 (1), 171-216.

[12] Spergel, D. N., et al. (2003). First-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: Determination of cosmological parameters. The Astrophysical Journal Supplement Series, 148 (1), 175.

[13] Kamionkowski, M., Kosowsky, A., & Stebbins, A. (1997). A probe of primordial gravity waves and vorticity. Physical Review Letters, 78 (11), 2058.

[14] Zaldarriaga, M., & Seljak, U. (1997). All-sky analysis of polarization in the cosmic microwave background. Physical Review D, 55 (4), 1830.

[15] Seljak, U., & Zaldarriaga, M. (1997). Signature of gravity waves in the polarization of the microwave background. Physical Review Letters, 78 (11), 2054.

[16] Abazajian, K. N., et al. (Simons Observatory Collaboration). (2016). The Simons Observatory: Science goals and forecasts. arXiv:1610.02743.

[17] Hazumi, M., et al. (LiteBIRD Collaboration). (2019). LiteBIRD satellite: JAXA's new strategic L-class mission for all-sky surveys of cosmic microwave background polarization. Journal of Low Temperature Physics, 194 (5), 443-452.

[18] Abazajian, K. N., et al. (Simons Observatory Collaboration). (2016). The Simons Observatory: Science goals and forecasts. arXiv:1610.02743.

[19] Hazumi, M., et al. (LiteBIRD Collaboration). (2019). LiteBIRD satellite: JAXA's new strategic L-class mission for all-sky surveys of cosmic microwave background polarization. In Journal of Low Temperature Physics (Vol. 194, Issues 5-6, pp. 443-452). Springer Science and Business Media LLC.

[20] Planck Collaboration. (2020). Planck 2018 results. I. Overview and the cosmological legacy of Planck. Astronomy & Astrophysics, 641, A1.

[21] CMB-S4 Collaboration. (2016). CMB-S4 Science Book, First Edition. arXiv:1610.02743.

[22] Berera, A. (1995). Warm inflation. Physical Review Letters, 75 (18), 3218.

[23] Bartrum, S., Bastero-Gil, M., Berera, A., Cerezo, R., Ramos, R. O., & Rosa, J. G. (2014). The importance of being warm (during inflation). Physics Letters B, 732, 116-121.

[24] McAllister, L., & Silverstein, E. (2008). String cosmology: A review. General Relativity and Gravitation, 40 (2), 565-605.

[25] Conlon, J. P. (2006). The QCD axion and moduli stabilisation. Journal of High Energy Physics, 2006 (05), 078.

[26] Planck Collaboration. (2020). Planck 2018 results. I. Overview and the cosmological legacy of Planck. Astronomy & Astrophysics, 641, A1.

[27] Planck Collaboration. (2020). Planck 2018 results. V. CMB maps. Astronomy & Astrophysics, 641, A5.

[28] Suzuki, A., et al. (LiteBIRD Collaboration). (2018). The LiteBIRD Satellite Mission: Sub-kelvin Instrument. Journal of Low Temperature Physics, 193 (5), 1048-1056.

[29] Bobin, J., Starck, J. L., Sureau, F., & Basak, S. (2013). Morphological component analysis and inpainting on the sphere: Application in physics and astrophysics. Journal of Fourier Analysis and Applications, 19 (5), 878-900.

[30] Baumann, D., & McAllister, L. (2015). Inflation and String Theory. Cambridge University Press.

[31] Linde, A. (2005). Particle physics and inflationary cosmology. Contemporary concepts in physics, 5, 1-362.

[32] Goldwirth, D. S., & Piran, T. (1992). Initial conditions for inflation. Physics Reports, 214 (4), 223-291.

[33] Cirelli, M. (2012). Indirect Searches for Dark Matter: a Review. Pramana, 79 (5), 1021-1043.

[34] Fields, B. D., Molaro, P., & Sarkar, S. (2014). Big-Bang nucleosynthesis: Connecting inner space and outer space. Frontiers of Physics, 9 (6), 690-719.

[35] Clifton, T., Ferreira, P. G., Padilla, A., & Skordis, C. (2012). Modified gravity and cosmology. Physics Reports, 513 (1-3), 1-189.