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CMB Polarization as a Probe for Inflationary Cosmology

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Abstract:

This paper discusses some information about the cosmic microwave background radiation (CMB)'s polarization and the study of the early state of the universe. The early state of the universe. The heat emitted after the Big Bang is called the CMB, and the CMB polarization carries important information about the shape and structure of the early universe and is an important means to study the state of the early universe. This paper first introduces the background knowledge of CMB, and then discusses the theoretical framework of inflation theory, including some important concepts and different models of inflation theory, specific CMB polarization modes, and some specific techniques for analyzing CMB polarization data. Next, the paper discusses the observational evidence for the CMB, including important experiments such as WMAP, Planck, and BICEP, and their support for inflation theory. The paper also introduces the data analysis method of CMB polarization.

Keywords: CMB; polarization; cosmology; Inflation.

1. Introduction

1.1 Background

The CMB is the earliest radiation in the universe, and it is the thermal radiation produced and retained after the Big Bang. Therefore, the detection of the CMB has great implications for the origin and evolution of the universe. In the beginning, it wasn't microwave radiation, but became what it evolved as the universe cooled and redshifted to what it is today. The CMB, a radiation that fills almost the universe, is uniform and has a temperature of about 2.7K. The discovery of the CMB provides evidence for the Big Bang theory, and the CMB itself is very uniform, it is considered an important factor in cosmology, and much research revolves around the CMB. Of course, the CMB is not perfectly uniform, and it has extremely small temperature fluctuations, which are considered evidence of density fluctuations in the early universe and the source of later star and galaxy formation.

1.2 Obiectives

In the CMB, polarization is a field used to study those that carry important information about the early processes of the universe. In inflation theory, CMB polarization has two different polarization modes, which are called B-mode and E-mode respectively. Regarding the first part, E-mode polarization carries information that causes density changes in the universe, which existed in the early universe and is

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recorded by E-mode polarization. About E-mode polarization, it also a polarization mode that has been discovered and recorded by data. By studying E-mode polarization, scientists can better understand the information the initial conditions of the formation of the universe and of large-scale structure of the universe. In the inflationary model, the birth of gravitational waves is believed to have occurred during inflation, so the observation of B-mode polarization is considered to be evidence of the existence of primordial gravitational waves, and the study of this polarization helps to understand the fundamental physical processes and sources of the universe.

2. Theoretical Framework

2.1 Inflationary Cosmology

Inflation cosmology is a central theory in modern cosmology, which explains the period of rapid inflation in the universe. The theory was proposed by American physicist Alan Guth in 1981[1], and since then it has been developed and refined by many physicists.

Inflationary cosmology holds that in a short period of time after the Big Bang, an exponential expansion occurred in the universe, which is called inflation. The theory is used to solve the event horizon problem in the standard Big Bang model and the flatness problem in the cosmic microwave background.

The core of inflationary cosmology lies the inflationary field, a hypothetical scalar field with a high energy density that is the driving force behind the exponential expansion of the universe. In the early universe, its energy density was much higher than it is now, its potential energy is driving the expansion of the universe. This happens when the expansion field drops from a high potential state to a low potential state, inflation ended, and after that, the universe entered a period of cooling and matter formation.

Under this theoretical framework, there exist a series of important theoretical models, including the New Inflation Model, Chaotic Inflation Model and Hybrid Inflation Model. These models all attempt to describe more precisely the mechanisms by which inflation occurs and its effects on the structure of the universe.

2.2 CMB Polarization

Inflation theory makes many predictions, three of which are important. First, inflation explains that the universe should be flat on large scales, which means that the universe follows Euclidean geometry rather than non-Euclidean geometry. Second, inflation theory predicts the temperature fluctuation pattern of the CMB, which predicts that quantum fluctuations during expansion were amplified to classical scales to determine the CMB's temperature fluctuation patterns. Third, inflation theory predicts the creation of primordial gravitational waves due to quantum fluctuations in space-time itself during inflation.

The two polarization patterns of the CMB in inflation theory correspond to two predictions about temperature fluctuation patterns and primordial gravitational waves, one is mode E and the other is mode B, where the E-mode is a polarization mode similar to the electric field line, and it is caused by density perturbations, which are amplified in inflation and translated into the temperature fluctuations and E-mode polarization of the CMB. The other, B-mode polarization is thought to be caused by primordial gravitational waves formed during expansion, leaving a special vortex polarization pattern in the CMB, and it is feasible for E-mode and B-mode to be confirmed or falsified in measurements.

The first and second predictions were observed, but the third was not. BICEP2 announced in 2013 that it had detected such a signal, but in a joint paper published in 2015, the researchers noted that The previously observed B-mode signal strength can largely be explained by the contribution of galactic dust, so there is no actual observational evidence for the B-mode.

3. Observational Evidence

3.1 Techniques for Measuring CMB PolarizatiorInstruments and missions

It will provide observations of the flatness and temperature fluctuation patterns predicted in inflation theory, several important projects are the WMAP satellite, the Runk satellite and the Background Imaging of Cosmic Extragalactic Polarization (BICEP) set of experiments, WMAP and Planck satellites were used to scan the entire sky to measure the CMB's polarization and temperature distribution. WMAP carries the microwave anisotropic radiometer, which contains a series of microwave detectors capable of picking up the CMB signal at different frequencies. The Planck satellite has two main scientific instruments, the Low Frequency Instrument (LFl) and the High Frequency Instrument (HFI), which operated over a wide frequency range to accurately measure the CMB's temperature and polarization. Compared to WMAP, which was launched in 2001, and Planck, which was launched in 2009, Planck provides a higher resolution map of the CMB's temperature and polarization than WMAP. BICEP is a series of ground-based telescopes at the South Pole that are being used to detect the CMB's polarization patterns. BICEP's scientific instruments are highly sensitive cryogenic detectors that capture the polarization of the photons of the CMB.

3.2 Detection of Polarization PatternsObservational data supporting inflation

The Planck satellite makes precise measurements of the temperature and polarization of the CMB, and its observations support the inflation theory. In a recent study, using the Planck satellite data set from 2015, the probability of the tail. Tail was 3.68%, which is relatively low, when combined with the temperature and polarization data. In addition to being within the statistically acceptable range [2], the cosmological parameters were precisely constrained by the Planck data, which revealed the anisotropy of the CMB in both temperature and polarization. The final data set from the Planck satellite was released in 2018, which supported the inflation model and defined precise measurements of several key cosmological parameters.

Another important project, BICEP2, observed a higher-than-expected B-mode power [3] in the multipole (ℓ) range of 30 to 150. This unexpected signal is consistent with predictions of gravitational waves produced during inflation, which leave a distinctive the signal of B-mode polarization in the CMB. This was initially thought to be direct evidence for the existence of primordial gravitational waves, but a subsequent joint analysis in 2015 found strong evidence that the observed B-mode polarization signal was primarily caused by galactic dust, rather than primordial gravitational waves. An upper limit on the tensor modulus is given, that is, a ratio r less than 0.12 [4] at the 95% confidence level indicates that these signals are at least partly caused by galactic dust pollution, and cannot be confidently said to be evidence of primary gravitational waves.

4. Analytical Methods

4.1 Data Analysis Techniques

Some models are introduced here, such as the data analysis used in a paper [4] to verify whether B-mode polarization is primarily caused by primary gravitational waves. The re-smoothing of Planck maps to match the BICEP2/Keck beam profile and the estimation of TT, TE, EE and BB power spectra using standard CMB analysis techniques such as the pseudo-beam (anafast), alteralm and synfast programs, this was tested using simulated data sets. These simulations include CMB signals, noise, and dust contamination to ensure the reliability of the analytical method when working with real data. Another paper discussing the scientific significance of CMB and data analysis issues [5] states that Tensor Spherical Harmonics, because polarization is not a scalar, cannot be expanded simply by spherical harmonics like temperature changes, but can be expanded by tensor spherical harmonics. These methods turn signals received by scientific instruments like the Planck satellite into validation of theories that more effectively distinguish between dust contributions in the CMB and possible inflationary gravitational wave signals.

4.2 Modeling Inflationary Signals

In this section some models of inflation theory will be listed.

The first inflation model, proposed by Guth in 1981, states that the horizon and flatness problems would have been solved when the universe had been too cold in its early history to be many orders of magnitude below the critical temperature [1].

The next improvement on this model was a new model proposed by A.D. Linde, which took into account phase transitions under the Coleman-Weinberg mechanism, which could avoid the problem of the universe becoming heterogeneous and anisotropic after a phase transition in the previous model [6].

The other is the Kachru-Kallosh-Linde-Trivedi (KKLT) model, which starts with the construction of de Sitter vacuums in string theory and finds that the lifetimes of these vacuums can be very long, beyond the cosmological time scale, enough to meet the cosmological lifetime requirements [7].

5. Results

5.1 Insights from E-mode Polarizatior

One of the models of inflation used to study the early universe's density fluctuations is the CMB's E-mode polarization, which is related to scalar density perturbations in the universe.

In the polarization pattern, the polarization vector of this pattern is at a certain point in the sky, and its direction is the electric field vector along the shortest path between two points. This pattern can be identified in the CMB's polarization. The distribution of the polarization of the E pattern provides important information for the study of the early conditions of the universe and the determination of cosmological parameters.

The E-Mode project is a means of detecting density fluctuations and large-scale structures in the early universe, which are the source of large-scale structures in the universe today. By measuring the polarization of the

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E-mode, the standard cosmological model Lambda Cold Dark Matter (ΛCDM) can be tested. In addition, accurate measurement of E-mode polarization also contributes a lot to understanding the early dark energy of the universe, which leaves traces in the CMB EE power spectrum, and high-precision CMB polarization data can help researcher better understand cosmological models and the early evolution of the universe.

5.2 Insights from B-mode Polarization

Another CMB polarization mode is B-mode polarization, is directly related to primordial gravitational waves, the observation of B-mode polarization is considered evidence of primordial gravitational waves. According to general relativity, the universe produces Primordial gravitational waves during inflation, and these waves leave a specific polarization pattern in the CMB, known as B-mode polarization, which has a curl characteristic that E-mode polarization does not have.

An important prediction in inflation theory is the local existence of gravitational waves, and if B-mode polarization can be observed, it can prove the existence of primary gravitational waves and support inflation theory. The observation of B-mode polarization can also further verify the correctness of general relativity. Since B-mode polarization is caused by primordial gravitational waves, it can be used to explore the early density fluctuations and temperature distributions of the universe.

6. Discussion

6.1 Interpretation of Findings

As an important model, the inflation model provides an explanation for the rapid expansion of the early universe, and explains the flat type problem and the event horizon problem.

Inflation theory also predicts tiny temperature fluctuations in the cosmic microwave background due to quantum fluctuations during inflation. These fluctuations are thought to be the seeds of all future cosmic structures, such as galaxies and galaxy clusters, because microscopic perturbations are amplified on a macroscopic level during inflation.

On the other hand, the theory of inflation has promoted the research of cosmology, high energy physics and particle physics. At the same time, inflation theory has provided new observation targets and theoretical tools for cosmology.

6.2 Comparison with Theoretical Predictions

As an important theory in modern cosmology, inflation model has many scientists studying whether it has enough evidence to support it. Criticism of inflation theory mainly focuses on the problem of fine tuning. For example, the inflation model does not completely solve this problem while replacing the fine tuning initial conditions of Hot Big Bang model. Instead, it is transferred to the initial conditions of the expansion itself [8]. On the other hand, with the latest CMB data, including those from WMAP, ACT, and Planck 2013, challenging the classical inflation theory, these data no longer support the simplest potential expansion model, but favor a new model that requires more parameter adjustment [9].

However, there is also an alternative view of cosmic fine-tuning, which suggests that some celestial structures and cosmic processes can operate despite large occurrences of fundamental constants. In general, criticism of inflation has focused on fine-tuning, and although inflation is controversial on fine-tuning, it remains an important theory in modern cosmology.

6.3 Limitations and Challenges

Regarding the theory of inflation and the detection of CMB polarization, at this stage, many technologies and means are not satisfactory, for example, in many aspects, there are limitations to the detection of CMB polarization, which can be mainly divided into four aspects.

First, from the perspective of data acquisition, dust in the Milky Way can produce similar polarization, the polarization pattern of these dust is similar to that of CMB polarization, so it may obscure or distort the CMB signal, and the other is experimental error, which requires extremely high accuracy to measure CMB polarization. Existing satellites and other scientific equipment may not have enough close reading to detect the CMB's polarized signal.

From the perspective of data processing, the extraction of polarization information from CMB data requires complex data processing technology, including removing noise and atmospheric interference, etc. Therefore, there is no good enough method for data analysis, which will also lead to uncertainty. Finally, because inflation theory itself has many different models, the CMB polarization patterns predicted by different models may also be different.

These problems are not insurmountable, and as technology advances, each of the factors that contribute to uncertainty will reduce their impact on theoretical models. For example, the development of more sophisticated detection instruments can improve the quality and accuracy of data, and the development and use of more advanced data analysis techniques can more accurately extract polarization signals from CMB data.

7. Summary

There are many important and well-known results in the study of CMB polarization, including the prediction of the primordial gravitational wave inflation model, which was confirmed by looking for polarization signals, E-mode polarization was first detected by ground and balloon experiments, and with the launch of satellites like Planck, scientists have obtained more accurate data about E-mode polarization. B-mode polarization has not yet been detected, but there are still many projects, such as BICEP2 or the future CMB-S4, to detect the B-mode polarization of the CMB.

In terms of data analysis, CMB polarization has many data analysis techniques, and with the progress of technology, more analysis methods are applied to this field. For example, some technologies are used to remove the foreground pollution caused by cosmic dust.

At present, the exploration of CMB polarization is still an unexplored field, and many new exploration missions will be launched in the future, especially the B-mode polarization of CMB. For the time being, there is no conclusive evidence to prove the existence of B-mode polarization. Therefore, many projects are devoted to finding signals of B-mode polarization, such as CMB-S4. It plans to conduct seven to ten years of observations at the North and South Poles to search for primordial gravitational waves, and BICEP, for example, will continue to look for polarizing signals in the future.

In the future, there will also be many new technologies to support the exploration of CMB polarization, such as using more efficient superconducting transition edge sensor (TES) to improve the exploration ability of B-mode polarization, or building a larger scale detector array to improve the measurement accuracy of CMB polarization signals. Some recent techniques, such as an improved projection removal of polarized signals at foreground moments during reconstruction, which is a way to reduce foreground pollution of the galaxy, while also controlling the increase in noise [10], will be applied to the detection of CMBS in the future.

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