Analysis of the Principle, Facility and Observation Applications for CMB Detection

Ruochen Gu*

School of Basis, Independent Mclean, McLean, United States

*Corresponding author: sxf1978@suda.edu.cn

Abstract. The CMB, or Cosmic Microwave Background Radiation, stands as a cornerstone in the evolving understanding of the universe's fabric. This piece traces the CMB's journey, starting from its unexpected discovery by Arno Penzias and Robert Wilson back in 1964, which went on to play a crucial role in validating the Big Bang theory. Further, it unravels the challenge of the isotropy dilemma and sheds light on how inflation theory provided clarity. The CMB's significance spans a broad spectrum, offering a window into the primordial state of the universe, revealing nuances about density shifts and gravitational waves, and influencing realms like particle physics and cosmology. The study also touches upon the exciting strides being made in CMB studies, underscored by refined research methods and analytical advances. Additionally, the article underscores the CMB's contribution of the determine cosmological parameters, with a specific focus on employing the Sunyaev-Zel'dovich effect and the CMB's angular power spectrum to ascertain the Hubble constant (H0). As one looks ahead, further observations, increased precision, and refined calibration techniques hold the promise of advancing the comprehension of the CMB and its pivotal role in the realm of cosmology.

Keywords: CMB, inflation theory, cosmological parameters, Hubble constant, early universe.

1. Introduction

The investigation of Cosmic Microwave Background represents a domain rich in historical context and profound significance within the realm of cosmology [1]. In 1964, a landmark discovery was made by Arno Penzias and Robert Wilson when they identified the CMB. This not only corroborated the theory of an ancient, hot, and dense universe, but it also offered strong support for the authenticity of the Big Bang theory [2]. This serendipitous revelation opened a doorway to a universe of inquiry that would fundamentally reshape the understanding of cosmic origins. A central enigma that emerged was the remarkable isotropy of the CMB, with the exception of a dipole pattern attributable to the cosmic motion. This extraordinary uniformity raised a perplexing question, i.e., how is it that regions of the Universe, which were fundamentally disconnected causally during the epoch of CMB formation, exhibit such an exceptional temperature uniformity. This conundrum is commonly referred to as the isotropy, homogeneity, or horizon problem [3].

The solution to this isotropy puzzle was ultimately found in the theory of inflation, which posits a phase of rapid, exponential cosmic expansion during the universe's infancy. Inflation, a theoretical framework of remarkable elegance, resolved the horizon problem by orchestrating the collision of disjoint regions of spacetime prior to the emission of the CMB, thereby ensuring their thermal equilibrium and isotropy. The importance of CMB research is multifaceted. Firstly, it affords us a direct glimpse into the primordial Universe when it was a mere 300,000 years old, encapsulating a pivotal moment in cosmic history. Secondly, the CMB serves as a repository of crucial data regarding the primordial density fluctuations and gravitational waves engendered during the epoch of inflation. The analysis of these measurements facilitates rigorous tests of inflationary theory and provides crucial insights into the geometric properties of the Universe [4], including its curvature and overall density. Moreover, the CMB's polarization patterns hold the potential to offer decisive evidence of the gravitational waves predicted by inflation, enriching the understanding of the early cosmos.

The study of the CMB not only holds paramount importance in cosmology but also impacts particle physics significantly. It offers insights into potential signs of topological flaws, the early universe's magnetic fields, and various potential dark matter entities. Additionally, it provides constraints regarding the properties of large neutrinos, WIMPs, axions, the nature of vacuum energy, decaying matter particles, cosmic baryon imbalance, and ultra-powerful cosmic rays. As such, experiments focused on the CMB are instrumental in validating these theoretical ideas and pushing the boundaries of the understanding of the universe's physics. Recent progress in CMB research has ushered in a new era of profound comprehension concerning the CMB's role in unraveling the mysteries of the universe. These advancements in CMB investigations are characterized by enhancements in experimental techniques and data analysis methods. Notably, while data from CMB observations a decade ago, such as the WMAP 2007 results [5], harmoniously supported the widely accepted 6-parameter ΛCDM model, the past ten years have witnessed a remarkable surge in sensitivity and resolution. This surge has empowered researchers to explore extensions and adjustments to the existing model. CMB research is primarily driven by the quest to unravel the mysterious initial conditions of the universe, laying the groundwork for structure formation, as well as deciphering the intrinsic properties of its elemental components, such as neutrinos [4]. Investigations into the CMB bridge the gap between astrophysics and traditional physics, shedding light on the intricate journey from the universe's inception to the rise of its first cosmic entities.

Recent breakthroughs in CMB studies have illuminated the diverse traces left behind by different cosmic eras. These traces are molded by several elements, like gravitational lensing, the gravitational pull exerted by galaxy clusters, and their inherent motion [6]. Such discoveries have deepened the grasp of how the universe expands and how this expansion influences the evolution of vast cosmic structures. Regarding experimental techniques, a concerted effort is underway to harness the collective capabilities of an extensive array of detectors, whether they are ground-based or carried on balloon payloads. Moreover, the planning of new satellite missions, exemplified by initiatives like LiteBIRD and PIXIE [7-10], underscores the commitment to expanding the observational horizons. These remarkable advancements in observational capacity hold the promise of unlocking deeper insights into the CMB and its profound implications for cosmology.

2. Basic Description

The Cosmic Microwave Background (CMB) stands as a relic from the early universe, harkening back to a time when the cosmos had cooled to a temperature of around 3000 K during the recombination epoch. This period witnessed the momentous union of protons with free electrons, birthing atomic hydrogen and liberating the CMB as a byproduct of this decoupling phenomenon. Its presence echoes the prophetic assertions of the Hot Big Bang cosmological model, thereby cementing its status as a linchpin in the quest to comprehend the enigmatic origins of the universe. The CMB reveals itself as a subtle, nearly uniform radiance that gracefully permeates the vast expanse of the cosmos. Its pervasive isotropy, where it appears consistently uniform in all directions, encounters only sporadic interruptions in the form of subtle temperature variations, denoting anisotropies. These fluctuations in temperature assume monumental importance, for they encode invaluable insights into the universe's embryonic genesis and its subsequent journey through time and space.

A pivotal facet of CMB research hinges upon the comprehension of the thermalization process. This intricate phenomenon underscores the attainment of equilibrium between photons and the myriad cosmic particles, marking the pivotal juncture that ushered in the era of atomic hydrogen formation and the subsequent release of the CMB. A profound understanding of this thermalization process forms the bedrock of CMB investigations, unraveling the mysteries concealed within the CMB's anisotropies. Yet another facet of this multifaceted realm of exploration lies in the polarization anisotropies exhibited by the CMB. This characteristic pertains to the orientation of electromagnetic waves inherent in the CMB. The meticulous analysis of polarization augments the understanding of the early universe, unveiling critical insights regarding the presence of gravitational waves and the intricate history of ionization within the cosmos [10].

In the realm of data analysis pertinent to CMB research, the indispensable technique of binning takes center stage. This method involves the systematic categorization of data into specific temperature ranges and angular scales, enabling the intricate exploration of the statistical properties inherent to CMB anisotropies. Such an approach proves instrumental in decoding the nuanced features concealed within the rich tapestry of CMB data. Nevertheless, the CMB research landscape is not devoid of its challenges. Foreground contamination looms as a formidable adversary, stemming from extraneous emissions originating in various astrophysical sources. The presence of foreground contamination potentially introduces distortions that could compromise the precision of CMB anisotropy measurements. Hence, the development and implementation of robust methods aimed at mitigating this interference assume paramount importance, ensuring the extraction of authentic and unadulterated insights from CMB observations.

3. Principles

In the realm of measuring the temperature of the Cosmic Microwave Background (CMB), the detection principles are rooted in the use of velocity maps derived from data acquired by the WMAP, which is the short version of Wilkinson Microwave Anisotropy Probe, and sources from the FIRAS, also called Far InfraRed Absolute Spectrophotometer experiment. To grasp these principles, it's necessary to delve into the Doppler effect. As per the special theory of relativity, when observing the spectrum from a reference frame in motion relative to the source of a blackbody spectrum, there is a noticeable frequency shift. This shift in frequency, denoted as S(ν), can be mathematically expressed as [11]:

$$S'(v) = B\left(T\sqrt{\frac{1+v}{1-v}}, v\right) \tag{1}$$

In the context of measuring the CMBR temperature, the detection process revolves around adjusting the Far InfraRed Absolute Spectrophotometer (FIRAS) instrument using data from the Wilkinson Microwave Anisotropy Probe to generate velocity maps. These maps, derived from WMAP data, serve to recalibrate the velocity concerning the CMB's surface of last scattering. This recalibration process entails dividing the velocity maps by the CMB temperature to reestablish the velocity calibration. The FIRAS dataset encompasses the CMB as well as various foregrounds, and it is subjected to fitting against different templates designed to account for these foreground signals. To determine the temperature spectrum associated with the velocity of the solar system concerning the CMB, an average spectrum is computed from the velocity maps. This average spectrum is then fitted to ascertain the CMB temperature. It's worth noting that the primary source of uncertainty in temperature estimation is the noise inherent in the FIRAS measurements [12].

In summary, the fundamental principles guiding CMB temperature detection encompass the recalibration of the FIRAS instrument through the utilization of WMAP data to produce velocity maps. These maps are subsequently employed to derive the CMB temperature by fitting FIRAS data to various templates and generating an average spectrum linked to the solar system's velocity concerning the CMB. The primary factor influencing the uncertainty in temperature estimation is the noise within the FIRAS measurements.

4. Facilities: COBE, Planck and WMAP

The Cosmic Background Explorer (COBE) mission was designed for the in-depth analysis and measurement of both the CMB and the cosmic infrared backdrop [13]. For example, the FIRAS was designed exclusively to chart the CMB's spectrum, spanning wavelengths between 0.1 and 10 micrometers. Its accuracy was astounding, clocking in at roughly 0.1% of the CMB's maximum brightness. This tool had a spectral resolution of 6GHZ, or $0.2cm^{-1}$, and could pinpoint details with an angular resolution of 7 arcminutes. On a similar note, the Differential Microwave Radiometers were fine-tuned to spot variations in the CMB's spatial distribution. They showcased sensitivities of 0.15 mK at 53, 90 GHz and 0.3 mK at 31 GHz for every 7 arcminute section of the sky. The Diffuse Infrared Background Experiment (DIRBE) also played a significant role, capturing precise readings of the cosmic infrared background and exploring its spectral and spatial traits over a broad range of photometric bands, from 300 to 1 micrometers. The instruments crafted with great precision were crucial in gathering critical data and executing detailed measurements associated with the CMB and cosmic infrared background. Specifically, FIRAS verified the CMB's thermal spectrum as the Big Bang model had anticipated and undertook the first all-encompassing far-infrared spectral line survey of the entire sky. The DMR produced detailed all-sky representations of the microwave background, and concurrently, DIRBE utilized its advanced capabilities to amass comprehensive infrared data and create in-depth celestial maps.

The Wilkinson Microwave Anisotropy Probe mission is a seminal undertaking that has profoundly shaped the understanding of the cosmos. Within its comprehensive documentation, the mission's intricate design, optics, radiometry, and rigorous characterizations are meticulously detailed [14]. Moreover, it highlights the dedication to progress, evidenced by continual updates and enhancements across various data releases. Notably, the availability of data products is underscored, supported by a comprehensive Explanatory Supplement. Furthermore, the document unveils the culmination of the WMAP mission's endeavors, presenting the final nine-year maps and results [15], complete with updated characterizations, meticulous calibrations, and the unveiling of temperature and polarization sky maps. The challenges of isolating cosmic microwave background (CMB) anisotropy from foreground emissions are addressed, with provisions for new point source catalogs and foreground masks. A significant focus here is the profound impact of WMAP data on cosmological analysis, illuminating precise and accurate cosmological parameters that lend robust support to the inflationary flat ΛCDM model. In sum, the WMAP mission stands as an exemplary endeavor that has not only enriched the knowledge of the universe's intricacies but has also significantly bolstered the confidence in the prevailing cosmological models.

SPT-3G, the third-generation camera developed for the South Pole Telescope, represents a significant leap forward in the field of CMB polarization research. This advancement brings about increased mapping speed and heightened sensitivity. The key to this progress lies in its polarization-sensitive receiver, which facilitates the acquisition of high signal-to-noise measurements for individual modes. Consequently, SPT-3G can provide precise constraints on neutrino mass and improved measurements of the primordial signal. The camera's design incorporates several technological innovations. It features an upgraded wide-field optical configuration and incorporates multi-chroic pixels capable of detecting multiple observing bands within a single detector element. This innovation results in a remarkable twentyfold increase in mapping speed when compared to its predecessor. SPT-3G, from a scientific standpoint, sets out to achieve a number of crucial objectives. It aims to untangle the power spectra of lensing and inflationary B-modes, enhance restricts on the amplitude and shape of the primordial signal, and establish stringent limits on the cumulative mass of neutrinos, potentially reaching levels as low as 0.06 eV. Moreover, the mission endeavors to offer new insights into the epoch of reionization and to contribute to a deeper comprehension of large-scale structure through its collaboration with the Dark Energy Survey (DES). This comprehensive strategy ensures that SPT-3G assumes a central role in pushing the frontiers of CMB research and advancing the understanding of the universe [16].

The Planck satellite represents a medium-sized mission within the "Horizons2000" science program. Its primary mission objective revolves around the precise capture of the anisotropies in the CMB with unprecedented levels of sensitivity and angular resolution. This spacecraft is furnished with two specialized instruments: the Low-Frequency and High-Frequency (LFI and HFI), each operating at different frequencies, four for LFI and six for HFI, respectively. The overarching mission goals encompass providing significant insights into matters of cosmological and astrophysical significance, encompassing the testing of theories related to the early universe, unraveling the origins of cosmic structures, establishing values for cosmological parameters, and measuring the Sunyaev-

Zel'dovich effect (SZ) [17]. Additionally, Planck carries out an extensive survey of the sky, identifying various extragalactic and Galactic sources by analyzing their spectral characteristics. The mission's standard operational phase spans 14 months, during which it performs two complete sky scans (seen from Fig. 1).

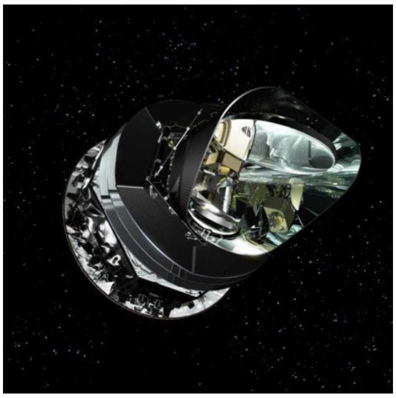

Fig. 1 ESA (Image by AOES Medialab)

5. Observations and Applications

Studying the CMB provides critical knowledge about cosmological parameters, notably the Hubble constant (H0) [18]. One prominent method to derive H0 utilizes the Sunyaev-Zel'dovich (SZ) effect. In this effect, Cosmic Background Background photons experience inverse-Compton scattering off the hot electrons present in the X-ray gas of galaxy clusters. Given that the SZ effect's intensity, roughly 1 mK, remains consistent irrespective of distance, it emerges as a potent means to measure H0, especially since a cluster's X-ray output depends on its distance. Advancements like ground-based interferometers and sharp X-ray spectra have further refined the capacity to measure the SZ effect. For precise H0 estimation, it's essential to examine the direct relationship between the SZ effect and electron density, as well as the squared relationship concerning X-ray emission. The deduced angular diameter distance plays a central role in defining H0. This methodology's merits are its relevance to cosmological spans within the Hubble flow. However, there are potential sources of error, such as assumptions of hydrostatic equilibrium, structural nuances, the intricacies of gas and electron density models, and projection effects. Recent studies merging Chandra X-ray with radio observations have proposed H0 values within 70.5-76.9 km s^{-1} Mpc^{-1}. The CMB is also pivotal for H0 estimation. The angular power spectrum of the CMB reflects acoustic ripples, with the peak locations mirroring the sound horizon during recombination. Though obtaining precise measures of the CMB's power spectrum is feasible, degeneracies can pose challenges in parameter deduction. H0 interacts with other parameters, necessitating independent H0 determinations to refine these parameters. Merging CMB insights with other datasets results in a consistent cosmological model, with H0 values approximately at 70.5 km s^{-1} Mpc^{-1}. Hence, techniques involving the CMB and the SZ effect are instrumental in enhancing the comprehension of the Hubble constant and the overarching cosmological narrative.

In the subsequent years, significant advancements occurred in the ability to narrow down the constraints related to the cosmological baryon density. A pivotal moment in this journey unfolded during the late 1990s when a team of researchers led by Scott Burles and David Tytler embarked on groundbreaking work, undertaking highly precise assessments of the primordial deuterium abundance. Their concerted efforts led to the determination of the baryonic abundance, denoted as Ωbh2, which was found to be approximately 0.020 ± 0.002 (at a 95% Confidence Level). This accomplishment represented a remarkable feat in achieving a level of precision that approached 10% [19]. Importantly, this outcome had significant implications for the understanding of the presence of baryonic Massive Compact Halo Objects (MACHOs) [20].

Explorations of the angular power spectrum of the CMB began revealing its potential to shed light on vital cosmological parameters. In particular, the varying heights of the alternating peaks in this spectrum were highly responsive to changes in baryonic density. While the late 1990s saw initial measurements of the second peak from ground-based and balloon-launched experiments, it was the advent of the WMAP satellite-based experiment that marked a turning point. This mission brought forth a precision in determining the baryonic density that was arguably superior to methods involving light element abundance assessments. The WMAP's data pointed to a baryon density value, Ωbh2, of roughly 0.02264 ± 0.00050 (at a 68% Confidence Level) [21]. Following this, a more recent assessment by the Planck Collaboration put forth a more stringent limit, suggesting Ωbh2 to be around 0.02225 ± 0.00016, reflecting a fractional uncertainty of under 1% [22]. When juxtaposed with the total matter density sourced from various experiments, it's clear that baryonic matter forms less than a fifth of the universe's total matter composition.

6. Limitations and Future Outlooks

The study encountered certain limitations due to the research team's decision to base their analysis on a subset of states observed by both the SPT and the Planck satellite, aiming to lessen the impact of sample variance [22]. This methodology suggests that the derived measurements might still be vulnerable to the influence of sample variance, marking a significant shortcoming. Looking ahead, the researchers emphasize the importance of further observations of the cosmic microwave background (CMB) temperature discrepancies at greater angular scales ($\ell > 2000$). Such observations would help identify possible departures from the ΛCDM model or inherent systematic mistakes. The team recommends analyzing the EE and TE CMB polarization power spectra from other telescopic sources to provide more rigorous assessments of the prevalent cosmological paradigm. As technological and instrumentational advancements emerge, they promise enhanced accuracy in gauging the CMB temperature power spectrum. Upcoming telescopes, like Advanced ACTPol, SPT-3G, and CMB-S4, are expected to produce superior data, paving the way for refined analyses of cosmological parameters. Moreover, addressing calibration uncertainties and potential distortions in the beam with heightened precision is paramount. Improved calibration methodologies and modeling frameworks are likely to reduce systematic inaccuracies, consequently boosting the reliability of cosmological parameter predictions.

7. Conclusion

In summation, investigating the Cosmic Microwave Background plunges researchers into a rich cosmological tapestry laden with historical milestones. The serendipitous unearthing of the CMB by Arno Penzias and Robert Wilson in 1964 stands as a watershed moment, bolstering the credibility of the Big Bang theory and reshaping the perception of the cosmos. Central to these explorations is the intriguing conundrum of isotropy, frequently termed the isotropy problem. The elegant resolution to this puzzle is presented by the inflation theory, suggesting a brief phase of accelerated cosmic expansion at the dawn of the universe. The study of the CMB is replete with layers of importance—it offers an unfiltered glimpse into the primordial state of the universe, acts as a treasure trove of insights on density variances and gravitational waves, and intertwines its revelations with the broader disciplines of particle physics and cosmology.Recent strides in CMB research signify a new era of comprehension, marked by advancements in experimental methods, data analysis techniques, and observational capabilities. Nonetheless, challenges persist, including the formidable issue of foreground contamination and lingering uncertainties. The detection and analysis of the CMB offer essential tools in the calculation of cosmological parameters, with a particular focus on the Hubble constant (H0). Notably, the Sunyaev-Zel'dovich effect and the CMB's angular power spectrum are instrumental in the pursuit of precise H0 determination. As one looks ahead, additional observations, enhanced precision, and refinements in calibration and modeling promise to further enrich the comprehension of the CMB and its pivotal role in advancing the understanding of the cosmos.

References

[1] Penzias A A, Wilson R W. A measurement of excess antenna temperature at 4080 MHz. A Source Book in Astronomy and Astrophysics, 1900–1975. Harvard University Press, 1979: 873-876.

[2] Kamionkowski M, Kosowsky A. The cosmic microwave background and particle physics. Annual Review of Nuclear and Particle Science, 1999, 49(1): 77-123.

[3] Kamionkowski M, Ratra B, Spergel D N, et al. CBR anisotropy in an open inflation, CDM cosmogony. arXiv preprint astro-ph/9406069, 1994.

[4] Spergel D N, Bean R, Doré O, et al. Three-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: implications for cosmology. The astrophysical journal supplement series, 2007, 170(2): 377.

[5] Staggs S, Dunkley J, Page L. Recent discoveries from the cosmic microwave background: a review of recent progress. Reports on Progress in Physics, 2018, 81(4): 044901.

[6] Ivezić Ž, Axelrod T, Brandt W N, et al. Large Synoptic Survey Telescope: From science drivers to reference design. Serbian Astronomical Journal, 2008 (176): 1-13.

[7] Spergel D, Gehrels N, Baltay C, et al. Wide-field infrarred survey telescope-astrophysics focused telescope assets WFIRST-AFTA 2015 report. arXiv preprint arXiv:1503.03757, 2015.

[8] Vavrek R D, Laureijs R J, Alvarez J L, et al. Mission-level performance verification approach for the Euclid space mission. Modeling, Systems Engineering, and Project Management for Astronomy VII. SPIE, 2016, 9911: 23-40.

[9] Naess S, Hasselfield M, McMahon J, et al. The Atacama cosmology telescope: CMB polarization at $200< \ell< 9000$. Journal of Cosmology and Astroparticle Physics, 2014, 2014(10): 007.

[10] Fixsen D J. The temperature of the cosmic microwave background. The Astrophysical Journal, 2009, 707(2): 916.

[11] Fixsen D J, Cheng E S, Gales J M, et al. The cosmic microwave background spectrum from the full cobe* firas data set. The Astrophysical Journal, 1996, 473(2): 576.

[12] Boggess N W. The Cosmic Background Explorer (COBE): Mission and Science Overview. Highlights of Astronomy, 1992, 9: 273-274.

[13] Spergel D N, Verde L, Peiris H V, et al. First-year Wilkinson Microwave Anisotropy Probe (WMAP)* observations: determination of cosmological parameters. The Astrophysical Journal Supplement Series, 2003, 148(1): 175.

[14] Kodali S K, Williams M R, Smith C R, et al. Two-year outcomes after transcatheter or surgical aortic-valve replacement. New England Journal of Medicine, 2012, 366(18): 1686-1695.

[15] Benson B A, Ade P A R, Ahmed Z, et al. SPT-3G: a next-generation cosmic microwave background polarization experiment on the South Pole telescope. Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VII. SPIE, 2014, 9153: 552-572.

[16] Tauber J A, Mandolesi N, Puget J L, et al. Planck pre-launch status: The Planck mission. Astronomy & Astrophysics, 2010, 520: A1.

[17] Bertone G, Hooper D. History of dark matter. Reviews of Modern Physics, 2018, 90(4): 045002.

[18] Burles S, Nollett K M, Turner M S. Big bang nucleosynthesis predictions for precision cosmology. The Astrophysical Journal, 2001, 552(1): L1.

[19] Fields B D, Freese K, Graff D S. Massive compact halo objects viewed from a cosmological perspective: Contribution to the baryonic mass density of the universe. New Astronomy, 1998, 3(6): 347-361.

[20] Bennett C L, Larson D, Weiland J L, et al. Nine-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: final maps and results. The Astrophysical Journal Supplement Series, 2013, 208(2): 20.

[21] Ade P A R, Aghanim N, Ahmed Z, et al. Joint analysis of BICEP2/Keck Array and Planck data. Physical review letters, 2015, 114(10): 101301.

[22] Aylor K, Hou Z, Knox L, et al. A comparison of cosmological parameters determined from CMB temperature power spectra from the south pole telescope and the planck satellite. The Astrophysical Journal, 2017, 850(1): 101.