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Understanding the Early Universe From the Cosmic Microwave Background

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Abstract:

The cosmic microwave background (CMB) is the faint glow of radiation left over from the Big Bang, providing crucial insights into the universe's history. Formed around 300,000 years after the Big Bang, the CMB consists of photons that have been traveling through space ever since, cooling down as the universe expanded. It was first detected in 1964 by physicists Arno Penzias and Robert Wilson, who discovered an unexplained background noise with their antenna, which turned out to be the CMB. This discovery marked the beginning of our ability to study the early universe through the temperature fluctuations in the CMB. Observations of the CMB have revealed critical information about the universe's spatial flatness and dark matter content, among other aspects. Understanding the CMB is essential as it provides a window into the universe's past and future. This paper explores the early universe's physics through CMB observations and aims to elucidate these concepts with plots from simulations. The focus will be on how CMB data reveals the universe's initial conditions, the formation of cosmic structures, and the role of the CMB in refining cosmological models, providing a deeper understanding of the CMB's significance and its impact on modern cosmology.

Keywords — **Astronomy, Cosmology, Cosmic Microwave Background, CMB**

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I. INTRODUCTION

Observation of the cosmic microwave background (CMB) provides evidence of a remarkable story: that we all came from quantum fluctuations! These are brief, random changes in the properties of a field or tiny particles [1]. These quantum fluctuations grew to create everything we know in the universe today. Learning more about the early universe through the CMB allows us to understand the physics of how this occurs.

In 1964, physicists Arno Penzias and Robert Wilson were trying to look for radio signals in the Milky Way, when they detected a signal in their satellite antenna that could not be attributed to any known source. They found it especially bizarre since this signal was coming from all directions with the same intensity, or in other words, that the signal was isotropic. This was the first detection of the CMB [2]. Scientists have since realized that these signals were radiation emitted from the beginning of the universe. The ripples and variations in this radiation carry information about the history of the universe and could help make predictions about its future.

II. EARLY UNIVERSE AND THE ORIGIN OF THE CMB

The discovery of the CMB led scientists to better establish the Big Bang Theory as the leading theory for the origin of the universe. This theory predicted that, in the very early universe, photons were tightly glued to matter. This early universe was extremely hot and dense; however, around 300,000 years after the Big Bang, the temperature dropped to about 3000 Kelvin, and atomic hydrogen began to form, resulting in the release of the photons from pieces of matter [3]. As the universe continued to expand and cool, these photons continued to travel freely throughout it, making up the CMB.

A. Temperature Maps & Power Spectrum

When the CMB was first discovered, it appeared to be exceptionally uniform throughout the sky; however, once satellites such as the Cosmic Background Explorer (COBE) [4] were developed to observe the CMB, scientists were able to measure temperature ripples within it. These ripples are traveling compressions and rarefactions of the gas that are heard as sound, and they mirror sound waves in the early universe. The sound spectrum formed by these waves contains information about the origin of fluctuations and the fate of the universe. What we see on small scales is actually sound due to the way in which CMB photons behave as a gas. They carry sound waves as gravity tries to compress the gas and pressure resists it. As this gas compresses, it becomes hotter, which is why we are able to see the sound rather than hear it.

The sound waves create hot and cold spots in the sky, which can be observed and used to create temperature maps that give us information about the early universe. These maps represent the spherical sky. When the CMB was first observed, the temperature map we saw was a monopole, showing that there were basically no variations in temperature at all. However, if the contrast of the map is increased, we are able to observe a dipole. The transition from observing a monopole to detecting a dipole in the CMB temperature map, facilitated by instruments such as COBE, illustrates the evolution of our ability to discern subtle temperature variations, offering insights into the early universe's dynamics. This map has maxima and minima pointing in opposite directions in the sky. At this level, the CMB temperature varies because of the motion of the Earth with respect to it. When the dipole is removed and the contrast is increased more, we are finally able to observe quantum noise in the universe. The variations in the map reveal variations in density within the early universe (see Figure 2). These density fluctuations were amplified by gravity and led to the formation of cosmic structures such as stars and galaxies. The hot and cold spots in the map are consistent with the quantum noise from inflation that formed structure through gravitational instability.

The sky map is divided into sections that are measured in degrees. At this scale, information about the formation of early structures in the universe is imprinted into the ripples of the map. In order to study this, we use a power spectrum of the temperature maps, which summarizes the information contained within the map by displaying power on different scales. The angular wavenumber or the multipole in this spectrum relates to the size of the features on the map. For example, when the angular wavenumber is set to $l = 100$, that means that the map is zoomed into a scale of about 1 degree. The angle, in degrees, is roughly given by $180 / l$. This allows us to study and comprehend the details of the early universe in a compact and interpretable form.

B. Temperature Maps & Power Spectrum

The thermal history of the universe tells us how it heats up and cools down over time. The universe is expanding, which means that everything is slowly moving away from everything else. As objects go further and further away, they appear to be receding faster, at a rate that is proportional to their distance. This is known as Hubble’s Law [5]. Accordingly, light waves of CMB photons get stretched as the universe expands. Just like how rubber bands lose strength when stretched out, as the wavelength increases, the wave’s energy decreases. Due to this diminishing energy, the CMB is slowly becoming colder, or redshifting. Likewise, if we go backwards in history, the photons get hotter, or blueshift. At around 3000 Kelvin, the CMB photons have enough energy to ionize hydrogen, turning it into a plasma. A plasma can be defined as a fourth state of matter. In a plasma, atoms are stripped of their electrons, resulting in a mixture of positively charged ions and free electrons. Even further back in time before the universe was this temperature, the universe was a hot mix of mostly electrons, protons, and CMB photons, with a small amount of helium and heavier elements containing neutrons. This is referred to as photon-baryon plasma [6].

In the plasma, free electrons play a crucial role by acting as glue, connecting CMB photons to the baryons, which include protons and neutrons. Thomson scattering and electromagnetic interactions are some of the processes by which these connections occur. Within the hot, dense environment of the early universe, pressure is a key factor, to which the photons contribute by exerting radiation pressure. This radiation pressure resists any attempt to compress the fluid, which sets up acoustic oscillations.

In the early universe, there were rhythmic patterns called acoustic oscillations. They arose when gravity compressed the photo-baryon fluid, but radiation pressure resisted it. This created areas with differing densities, with high-density areas making potential wells, and low-density areas making potential hills. In this case, the two scenarios were related to each other, and compression in the wells corresponded to rarefaction in the hills. The harmonics were diverse, with each wave acting differently. Shorter waves moved faster and vice versa for longer waves. However, during recombination when the baryons released the photons, the sound waves stopped, leaving behind peaks in the temperature of the CMB. Observing these variations helps us understand how things were moving in the early universe.

Acoustic oscillations caused variations in the CMB temperature across space and time. However, if they were observed around the time of recombination an observer would see the CMB at the same temperature everywhere. The wavenumbers of these oscillations, which freeze at their highest and lowest points over time, have a harmonic relationship. At recombination, the photon-baryon fluid stops shifting and essentially freezes, quickly changing from fluid behavior to streaming behavior. After this moment, the photons begin to stream freely and remain unaffected. As time goes on, we are able to receive radiation from more distant regions, allowing us to better understand the cosmic information encoded in the evolving temperature of the CMB. This freeze-and-stream scenario gives us valuable insights into the universe’s dynamic history.

III. ANISOTROPIES, POWER SPECTRUM, EXPERIMENTS [7]

Temperature anisotropies, which are fluctuations in temperature, in the CMB radiation reveal fascinating insights into the early universe's structure and evolution. These fluctuations, originating from quantum fluctuations during inflation, signify a remarkable narrative: our cosmic origins from quantum uncertainty. As all CMB photons have traversed roughly the same distance since the universe's recombination epoch, we can envision the CMB as emanating from a spherical surface, with us at the center. By increasing the contrast of a CMB map, the temperature variations, or anisotropies, are more clearly observable, providing crucial data about the universe's early conditions and the subsequent formation of cosmic structures.

C. COBE Satellite and the Discovery of Anisotropies

The COBE satellite made a groundbreaking discovery when it detected anisotropies in the CMB, revealing temperature ripples on angular scales ranging from 10 to 90 degrees. These large scales indicated that there was not enough time for cosmic structures to evolve, allowing COBE to essentially glimpse the universe's initial conditions. The power spectrum, which shows the size of fluctuations in relation to angular scale, indicated that COBE's angular scales were too broad to discern detailed structures. However, at much smaller angular scales, distinct acoustic peaks became visible in the power spectrum. COBE revealed a clear peak around a multipole value of $l \sim 200$, while potential evidence for expected features at higher multipoles was explored by subsequent experiments like Boomerang and Maxima. These experiments provided a closer look at the fine-scale structure of the CMB and the universe's early conditions.

D. Planck, ACT, and SPT: Current Main Measurements

The current main measurements of the CMB come from three key experiments. The Planck satellite, which has completed its mission, provided comprehensive data on the CMB. The ongoing experiments, the Atacama Cosmology Telescope (ACT) and the South Pole Telescope (SPT), continue to delve deeper into the fine-scale structures of the CMB. These experiments aim to refine our understanding of the universe's early conditions and contribute to the broader picture painted by COBE and other missions.

E. Upcoming Experiments: Simons Observatory and CMB-S4

Looking forward, large upcoming experiments, including the Simons Observatory (SO) and CMB-

S4, promise to further enhance our knowledge of the CMB. These experiments are expected to build on the foundations laid by COBE, Planck, ACT, and SPT, providing even more detailed insights into the early universe and its evolution.

F. FIRAS Instrument and the Blackbody Spectrum of the CMB

Another significant experiment that provided new information about the universe was the FIRAS instrument. Designed to precisely measure the CMB spectrum, FIRAS found that CMB radiation followed the pattern of a blackbody, an object that absorbs all radiation and then emits its own. The measurements taken by FIRAS allowed scientists to plot a graph of the spectrum, with the x-axis representing frequency and the y-axis representing the intensity of the emitted radiation. The discovery that the CMB is an almost perfect blackbody spectrum was crucial in understanding the nature of the early universe, as shown in Figure 1.

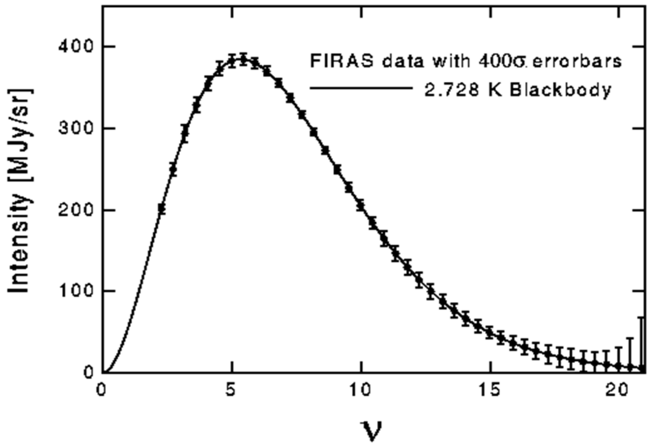

Fig. 1 Blackbody spectrum of the CMB measured with the FIRAS instrument. The x-axis is frequency, and the y-axis is intensity. This fit confirms the early universe's uniformity and supports the Big Bang model.

G. Visualizations

Building on the advancements from key experiments like COBE, Boomerang, Maxima, Planck, ACT, and SPT, we have gained deeper insights into the universe's early conditions and structure. They have given us the tools to represent the CMB in a more comprehensive way.

The CMB represents the afterglow from the beginning of the universe. When it is drawn as a map, we are able to observe temperature variations that contain clues about the early universe. The thermal Sunyaev-Zel'dovich (tSZ) effect [8] also provides insight about the universe’s origins. The tSZ map shows the scattering of CMB photons off hot electron gas within galaxy clusters, revealing the distribution of cosmic structures. We are able to obtain simulations of the maps from Websky [9]. Together, both the CMB map and the tSZ map provide important insights into the history of the cosmos.

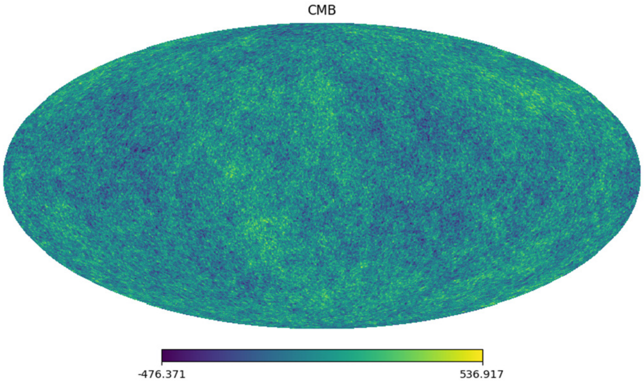

Fig. 2 CMB temperature map: Temperature fluctuations in the CMB, indicating early universe density variations. Color axis shows temperature from hot (yellow) to cold (purple).

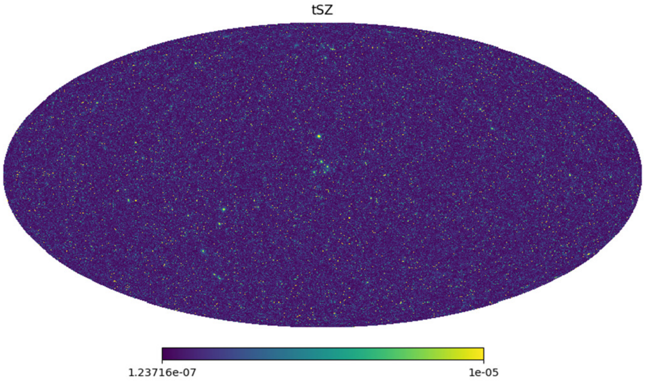

Fig. 3 tSZ temperature map: Scattering of CMB photons by hot electron gas in galaxy clusters. Color axis shows scattering intensity, revealing cosmic structures.

Using these maps, it is possible to compute their power spectra using the healpy software package [10].

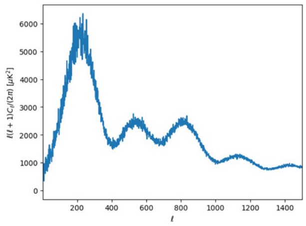

Fig. 4 CMB power spectra.

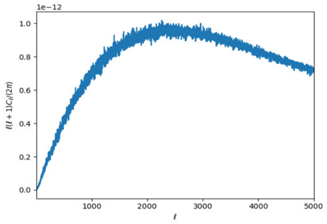

Fig. 5 tSZ power spectra.

Analyzing the power spectra of the CMB and tSZ maps is crucial for understanding the universe's structure. These spectra summarize how power is distributed across various angular scales, with the x-axis representing angular scales or multipole moments (l) and the y-axis showing power or amplitude. The spectra are calculated by decomposing temperature or intensity variations into different angular frequencies, where higher values indicate significant fluctuations at specific scales and lower values suggest less variation. The power spectra reveal the amplitude and scale of temperature fluctuations from the early universe, offering insights into its initial conditions, and show the clustering of cosmic structures and the distribution of power across scales. Comparing spectra from different maps and simulations helps scientists test theoretical models and refine our understanding of cosmological processes.

IV. CONCLUSIONS

The study of CMB radiation offers a profound journey into the early universe's history and evolution. From its accidental discovery in 1964 to the groundbreaking observations by satellites like COBE and Planck, our understanding of the universe's origins and dynamics has been greatly evolved. The temperature anisotropies in the CMB, originating from quantum fluctuations during inflation, provide invaluable insights into the universe's structure and development. Through analysis of CMB temperature maps and power spectra, researchers are able to uncover clues about the spatial flatness of the universe, the nature of dark matter, and the formation of cosmic structures.

Moreover, experiments like the FIRAS instrument have explained the CMB's blackbody spectrum, confirming its nature as the afterglow of the universe's birth. The complementary insights provided by the tSZ effect further enrich our understanding of cosmic structures and their distribution. This effect reveals how CMB photons scatter off hot electron gas within galaxy clusters, helping us map cosmic structures.

Looking forward, ongoing and upcoming experiments such as the Atacama Cosmology Telescope (ACT), the South Pole Telescope (SPT), the Simons Observatory (SO), and CMB-S4 promise to continue to deepen our understanding of the CMB and its implications for cosmology. These experiments are expected to refine our measurements, clarify our understanding of cosmic inflation, and enhance our knowledge of the universe's fundamental properties.

In essence, the cosmic microwave background serves as a time capsule, preserving vital information about the universe's early years and offering a glimpse into its future. By unraveling the mysteries encoded within the CMB, we continue to uncover the remarkable story of our cosmic origins and evolution.

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