THE PRINCIPLES AND DESIGNS OF COSMIC MICROWAVE BACKGROUND (CMB) EXPERIMENTS

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ABSTRACT

The cosmic microwave background (CMB) is one of our only sources of information about the earliest stages of the universe. According to the Big Bang theory, the universe was initially filled with a hot plasma of photons and subatomic particles. As the predicted modern-day remnant of this primordial plasma, the CMB offers some of the most compelling support for the Big Bang theory and is believed to carry information about the properties of the plasma and any earlier events that affected the plasma. In this paper, we explain how scientists extract cosmological information from data on specific characteristics of the CMB—including the energy scale of cosmic inflation, the density of matter and dark matter in the universe, and the Hubble constant—to verify their theories on the formation and evolution of the universe. We then describe the technological designs of important CMB experiments, focusing on how each experiment's specific design allowed it to make more accurate and precise measurements than its predecessors. Finally, we review the experiments' designs and achievements, looking for patterns to pinpoint what technological/design features future CMB experiments should have to further improve our measurements of the CMB and broaden our understanding of the early universe

1. INTRODUCTION

The cosmic microwave background (CMB) is a nearly uniform “glow” of radiation that is present throughout the universe and peaks in the microwave wavelengths of the electromagnetic spectrum. According to the Big Bang Theory, the universe began in an extremely hot, dense, and radioactive state filled with a photon-baryon plasma and has been expanding since its creation, distributing its heat/radiation and matter more evenly. Therefore, the CMB is one of the most compelling pieces of evidence for the Big Bang Theory: Scientists theorize that if the universe originated in a “Big Bang” 14 billion years ago, then the background radiation produced by this process should have redshifted (i.e. lost energy) to microwave wavelengths by the present day.

In 1965, Arno Penzias and Robert Wilson at the Bell Telephone Laboratories accidentally detected the CMB, providing the first observational evidence of the CMB and thereby also providing further support for the Big Bang Theory. Several estimates of the CMB’s temperature have been made over the years as more precise measurement tools became available; the most recent estimate is about 2.73 K [1]. The CMB is overwhelmingly isotropic (to 1 part in 100,000) in temperature, density, and other characteristics, which also supports the idea that it is a remnant of the Big Bang. It is very unlikely that distinct sources would produce radiation with such similar characteristics, which has led scientists to theorize that all the background radiation that constitutes the CMB originated from a single source—the Big Bang [2].

2. WHY IT IS IMPORTANT TO STUDY THE CMB

The CMB can reveal information about the early universe because it is a snapshot of the universe at the surface of last scattering—when photons broke free from subatomic particles when the universe was around 370,000 years old, releasing light into the universe for the first time. In its earliest stages, the universe was filled with a plasma of photons and subatomic particles; positively charged atomic nuclei were separate from negatively charged electrons because the high temperature of the universe made it so that electrons had too much energy to bind to protons. As the photons interacted with these charged particles, they were polarized (had their orientation changed) and often bound to the charged particles, leaving the universe completely dark. However, the universe eventually cooled to a temperature at which the photons and charged particles could no longer remain bounded—this event, known as the epoch of recombination or decoupling, lasted from around 18,000 years to 370,000 years after the Big Bang. As a result, the photons were allowed to travel freely through space and light up the universe; these photons are the radiation that redshifted into the CMB as their energy wore off over time. Thus, the CMB is simply a picture of the surface of last scattering, which means we can gain insight into the conditions of the universe during the epoch of recombination by measuring the CMB. After decoupling, atomic nuclei were also able to merge with electrons to form neutral hydrogen because they were no longer attached to photons [3].

The opacity of the surface of last scattering [4] acts as a sort of screen between us and any event in the universe that occurred prior to recombination: The light from the surface of last scattering blocks radiation from earlier events from reaching us, but contains imprints of many of these earlier events [5]. Thus, studying the CMB is currently our only mechanism of probing the earliest stages of the universe.

2.1. B-MODES & INFLATION

Mapping the CMB can also help confirm the occurrence and energy scale of inflation, or the period of rapid exponential expansion of the universe that is theorized to have taken place from 10^{-36} to 10^{-32} seconds after the Big Bang. Inflation is thought to have created gravitational waves that left their imprint on the landscape of the early universe in the form of a specific type of polarization called B-modes; if this is true, detecting B-modes in the CMB would be a strong indicator that inflation did occur. However, B-modes can also be created by gravitational lensing of CMB photons on their way to our telescopes, and the inflationary B-mode signal (which can be differentiated from gravitational lensing B-modes by a unique signature [6]) is predicted to be very low in amplitude and therefore may prove elusive. Scientists have not yet detected any inflationary B-modes in the CMB, but this task remains one of the most active and important areas in CMB research [7].

The inflationary theory is widely supported by physicists because it eliminates the need for very specific "initial conditions" that had to be present in the universe during the Big Bang in order for the universe to look the way it does today [2]. Thus, detecting inflation through the CMB would also provide further support for the Big Bang. Specifically, inflation explains 3 fundamental observations about our universe today that contradict what the Big Bang Theory alone predicts for the modern universe: The horizon problem, the flatness problem, and the magnetic monopole problem.

2.1.1. Horizon problem

The CMB's homogeneity is one of the main motivations for the inflationary theory. If 2 objects are in causal contact, it means they can communicate with each other because they are close enough for information to have traveled between in 14 billion years or less. However, we observe the CMB to have the same temperature almost everywhere, even in regions that are too far apart to be in causal contact; this raises the question of how these distant regions of the CMB were able to communicate and attain very similar properties.

Inflation solves this problem by proposing a way for all the matter and radiation from the Big Bang to be expanded to large scales while retaining its properties. Because the Big Bang occurred at a single point, all the components of the universe were once close enough to be in causal contact. Thus, different parts of the early universe photon-baryon plasma that gave rise to the CMB would have been able to communicate with each other and become mostly isotropic and homogeneous at this time before inflation expanded them out of causal contant. Inflation in particular is the only type of universe expansion that solves the horizon problem because a gradual expansion of space since the early universe would have given the primordial photon-baryon plasma enough time to fizzle out, and we would not see a CMB today. In contrast, the rapid, almost instantaneous nature of inflationary expansion would have preserved the photon-baryon plasma created in the Big Bang exactly as it was, simply scaling it up to huge sizes without changing its landscape too drastically [2].

2.1.2. Flatness Problem

The flatness problem refers to the fact that the density of matter and energy in the universe is very close to a particular “critical density,” which is considered an extremely unlikely coincidence. With the critical density, the expansion of the universe and gravitational attraction between different cosmic objects are balanced in such a way that the expansion of the universe eventually decelerates and stops but never reverses (i.e. the universe doesn’t collapse), which makes the universe flat. Inflation solves this problem because it is believed to have “smoothed out” the universe, removing any potential curvature (positive or negative curvature) it may have had and making it flat [2].

2.1.3. Monopole Problem

On the note of “smoothing out” the universe, inflation may also explain why we have not been able to detect magnetic monopoles, or magnets with only 1 pole, in the modern universe. The Big Bang theory predicts that the early universe was extremely hot, which is predicted to have merged the electromagnetic force, strong nuclear force, and weak nuclear force into a single force (called a Grand Unified Theory). The Grand Unified Theory that describes the primordial universe predicts that in such a high energy state, large amounts of heavy, stable magnetic monopoles should have been produced, but no such monopoles have been detected so far. Inflation would have diluted magnetic monopoles to such low densities that it is unlikely to find one in the modern universe, solving the magnetic monopole problem [2].

2.1.4. Inflation’s role in structure formation

Inflation is also theorized to have helped transform quantum fluctuations in the early universe into modern-day structure (stars and galaxies), which further emphasizes the value of studying the CMB to detect inflation. Inflation is believed to have expanded these quantum fluctuations into larger regions of the universe whose matter densities were higher or lower than average. These density inhomogenities created temperature and polarization fluctuations in the CMB. CMB photons in more dense regions had to expend more energy to break away from the gravitational pull of the region during decoupling, which means these photons are relatively cooler. The high gravity of overdense regions in the early universe also enabled them to accumulate material and subsequently increase their gravitational pull even further. The first stars are theorized to have originated from this early universe matter accumulation [8].

Temperature fluctuations in the CMB are also directly related to a type of polarization of CMB photons called E-mode polarization, which was also caused by interactions within the primordial photon-baryon plasma before decoupling: Thomson scattering of the photons by the charged subatomic particles changed the photons’ orientation [9].

On the whole, probing the CMB for B-mode polarization can help confirm or reject the theory of inflation, which could support or highlight the need for revisions in the Big Bang theory. Studying the temperature fluctuations and E-mode polarization can reveal information about what kind of density inhomogenities were present at the surface of last scattering, which can in turn tell us about quantum fluctuations and the overall conditions of the early universe.

2.2. TEMPERATURE AND POLARIZATION POWER SPECTRA

The temperature and polarization of different regions of the CMB can be measured and modeled as angular power spectra, which plot the intensity of temperature or polarization fluctuations over multipole moment—which indicates how “zoomed in” to the CMB the instrument is when taking the measurement, or what angular size on the sky the measurement was taken from [10]. Temperature fluctuations can be directly measured using radiometers and bolometers [11], which detect the power of electromagnetic signals (in this case, the CMB). Orthomode transducers detect the electrical fields emitted by the Q and U Stokes parameters that correspond to CMB polarization, then separate the polarization into E-modes and B-modes based on whether the signal is curl-free (E-modes) or divergence-free (B-modes). Antenna measure the strength of each polarization signal [9].

The average temperature of the CMB has been consistently measured to be about 2.725 K (although earlier measurements were less precise), and the temperature power spectrum of the CMB has been found to be nearly identical to that of a blackbody in thermal equilibirum. This suggests that the universe was in thermal equilibrium at the time of decoupling—a major piece of evidence for the Hot Big Bang model.

2.2.1. Baryon acoustic oscillations

Understanding the science behind temperature fluctuations in the CMB enables us to probe the peaks of this power spectrum for valuable information about early universe conditions. In regions of the early universe where matter was not dense enough to collapse into structures, gravitational attraction between the matter particles and outward-directed radiation pressure between photons were in a back-and-forth limbo, periodically overtaking each other [12]. As a result, the regions would oscillate between having high densities (when the gravity was stronger) and low densities (when the radiation pressure was stronger)—these fluctuations are called baryon acoustic oscillations (BAOs) [12]. Photons in denser regions had to expend more of their energy to overcome gravitational attraction with surrounding particles than photons in less dense regions because gravitational attraction is stronger when particles are closer together. Thus, photons that were in denser regions of the universe at the time of decoupling were colder than photons in less dense regions [8], and these differences in temperature are in fact the temperature fluctuations we see in the CMB. Examining the location of temperature fluctuations in the CMB therefore provides information on the distribution of matter in the universe at the time of decoupling—warmer regions of the CMB had a smaller density of matter than cooler regions.

On the CMB power spectrum, peaks occur where the density of a certain region is at the maximum or minimum of its acoustic oscillation cycle—these are the stages at which the temperature of the CMB deviates from the average most drastically, meaning the temperature fluctuation signal is strongest (although the fluctuations are still at the microkelvin level). Specifically, odd-numbered peaks correspond to regions that were at their maximum density at the time of decoupling, while even-numbered peaks correspond to regions at their minimum density at the time of decoupling. Taller peaks indicate stronger temperature fluctuation signals at their respective multipoles.

2.2.2. The density of matter and dark matter

As regions become more dense, their gravitational attraction increases. Subsequently, they attract and accumulate more material, thereby reducing the expansion effects of radiation pressure and becoming even more dense over time. Analysis of these peaks allows scientists to determine the concentration of baryonic and dark matter in the universe. At first, scientists expected the third peak of the temperature power spectrum to be shorter than the second peak; however, the third peak is actually slightly taller than the second peak, revealing that there was far more dark matter in the early universe than scientists previously thought [12]. Dark matter generates gravitational force but does not interact with photons, meaning it contributes to the inward pressure on nearby baryons but is unaffected by nearby photons' outward radiation pressure [12]. Therefore, more dark matter in the early universe means more overdense regions than underdense regions, which exactly translates into stronger odd peaks than even peaks on the CMB temperature power spectrum [12]. The presence of additional dark matter in the corresponding region would explain the unexpectedly large height of the third peak on the power spectrum.

After calculating the density of dark matter in the early universe, the ratio of the height of odd peaks to the height of even peaks can be used to calculate the density of baryonic matter in the universe at this time [12]. The location of the peaks on the power spectrum confirms these predictions for the amount of baryonic matter in the universe at the time of decoupling. If there were more protons and electrons at this time, the acoustic oscillations in the photon-baryon plasma would have been slower, meaning their minimum and maximum densities would have occurred at smaller angular scales; thus, we would have seen the power spectrum peaks at higher multipole moments.

2.2.3. Dark energy and the curvature of the universe

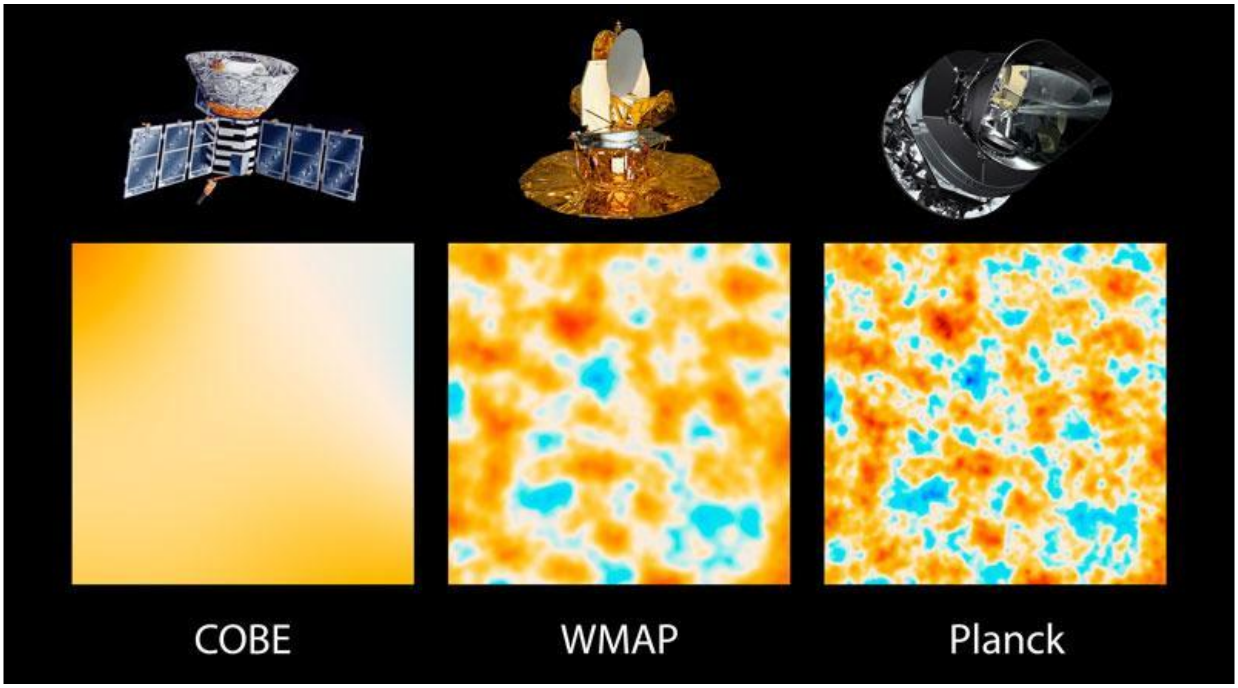
The temperature power spectrum peaks also support the existence of dark energy and the theory that the universe is flat. By causing universe expansion, dark energy limits structure formation. This means that if the universe had less dark energy, it would have more stars and galaxies and as a result, CMB photons would be deflected more from their original path by the time they reach the Earth [13]. Scientists can calculate the path that particular CMB photons would take to reach the Earth if there were no structure in the universe, and they can then compare this to the true path taken by these photons in order to determine how much the photons have been gravitationally lensed. Scientists have found that if there were no dark energy in the universe, the CMB photons would have undergone far more lensing than measured, implying that dark energy does exist [13]. The size of the CMB density fluctuations at the time of decoupling was dictated by how quickly density fluctuations could spread through the photon-baryon plasma. Scientists know that the acoustic oscillations could travel through the primordial photon-baryon plasma at the 60% of the speed of light (due to the properties of the plasma itself), and that these oscillations occurred for about 375,000 years because this is when decoupling happened and “froze” the oscillations in place. By multiplying this rate by this time, scientists can determine the distance the acoustic oscillations traveled and subsequently the original size of the CMB anisotropies they created [12]. Comparing this calculated size to the size that we observe certain CMB anisotropies to be, scientists have found that the universe must be flat: Because the geometry of the universe affects the path of photons through space, we would observe the CMB anisotropies to have different sizes depending on whether the universe is flat, positively curved, or negatively curved [12].

2.3. AUTOCORRELATIONS AND CROSS-CORRELATIONS

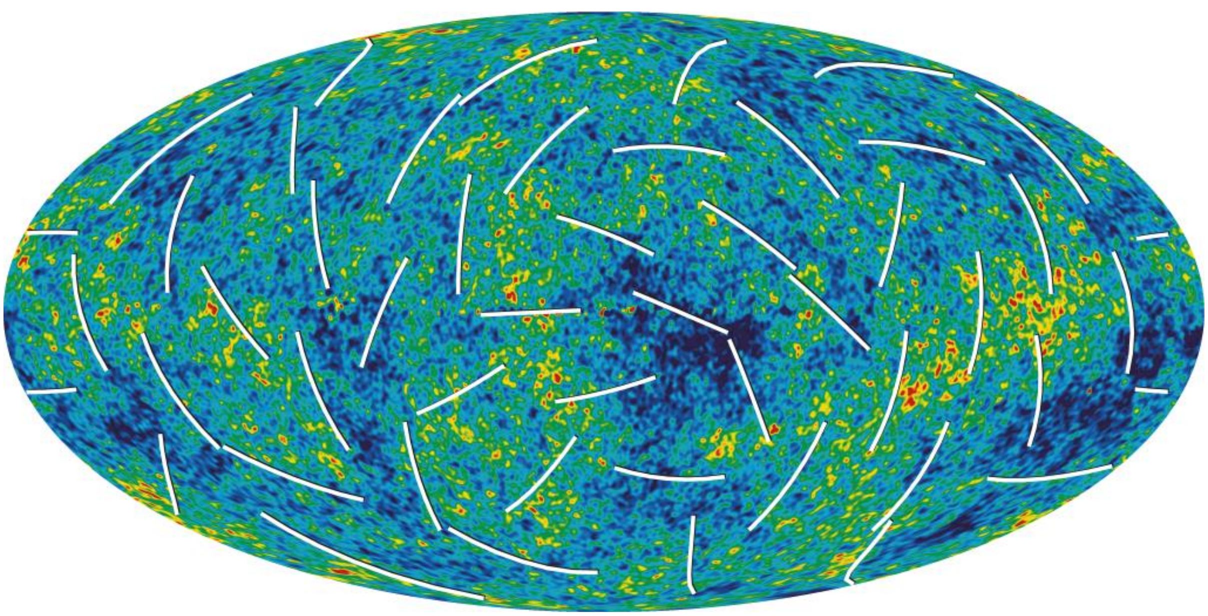
An especially useful tool in extracting information of CMB power spectra is auto- and cross-correlations, which has provided support for the BAO model. Autocorrelations essentially map power spectra of the same value on top of each other in order to amplify the data to make it easier to analyze; cross-correlations map power spectra of different values on top of each other to investigate relationships (or periodicities) between these values.

2.3.1. Sky maps

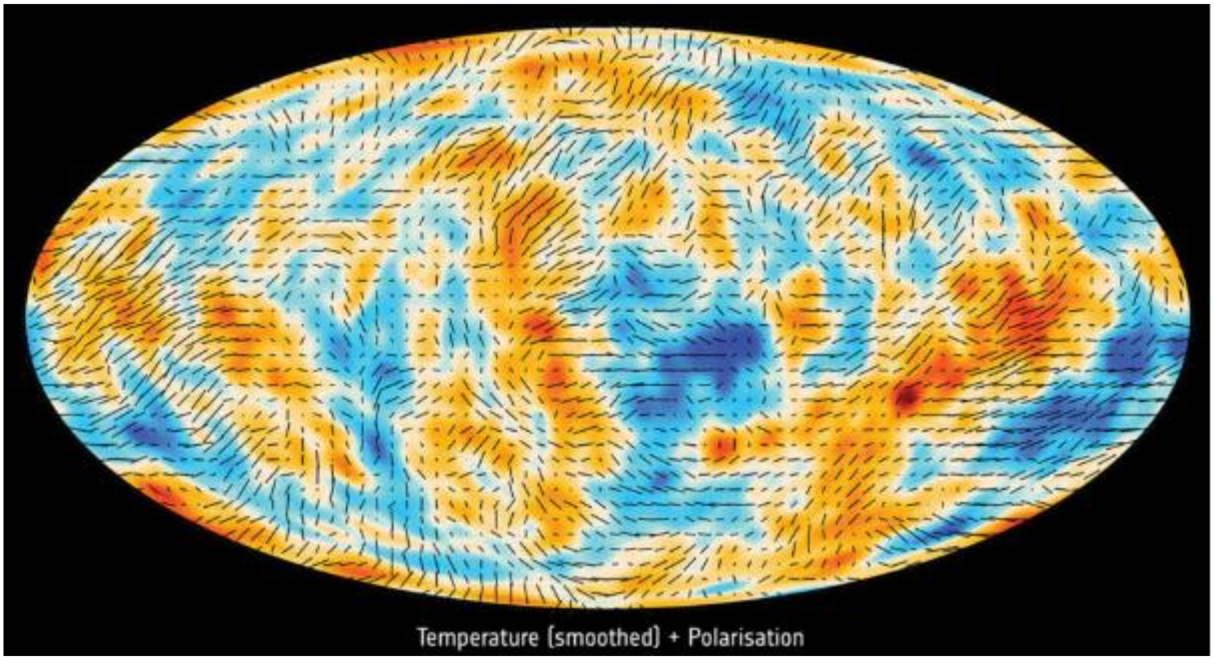
The Cosmic Background Explorer (COBE), the Wilkinson Microwave Anisotropy Probe (WMAP), and Planck were the first 3 major experiments in CMB science. Each experiment significantly improved on the precision/angular resolution of its predecessor, creating a more detailed map of the temperature and (E-mode) polarization anisotropies in the CMB. Pictured here are the temperature sky maps produced from COBE, WMAP, and Planck data respectively, followed by the polarization sky maps from WMAP and Planck:



Temperature maps of the CMB from COBE, WMAP, and Planck. Image from NASA/JPL-Caltech/ESA.



WMAP's polarization map overlaid on the temperature map. Red represents warmer spots, while blue represents cooler spots, and the white lines indicate the polarization direction. Image from NASA/WMAP Science Team.

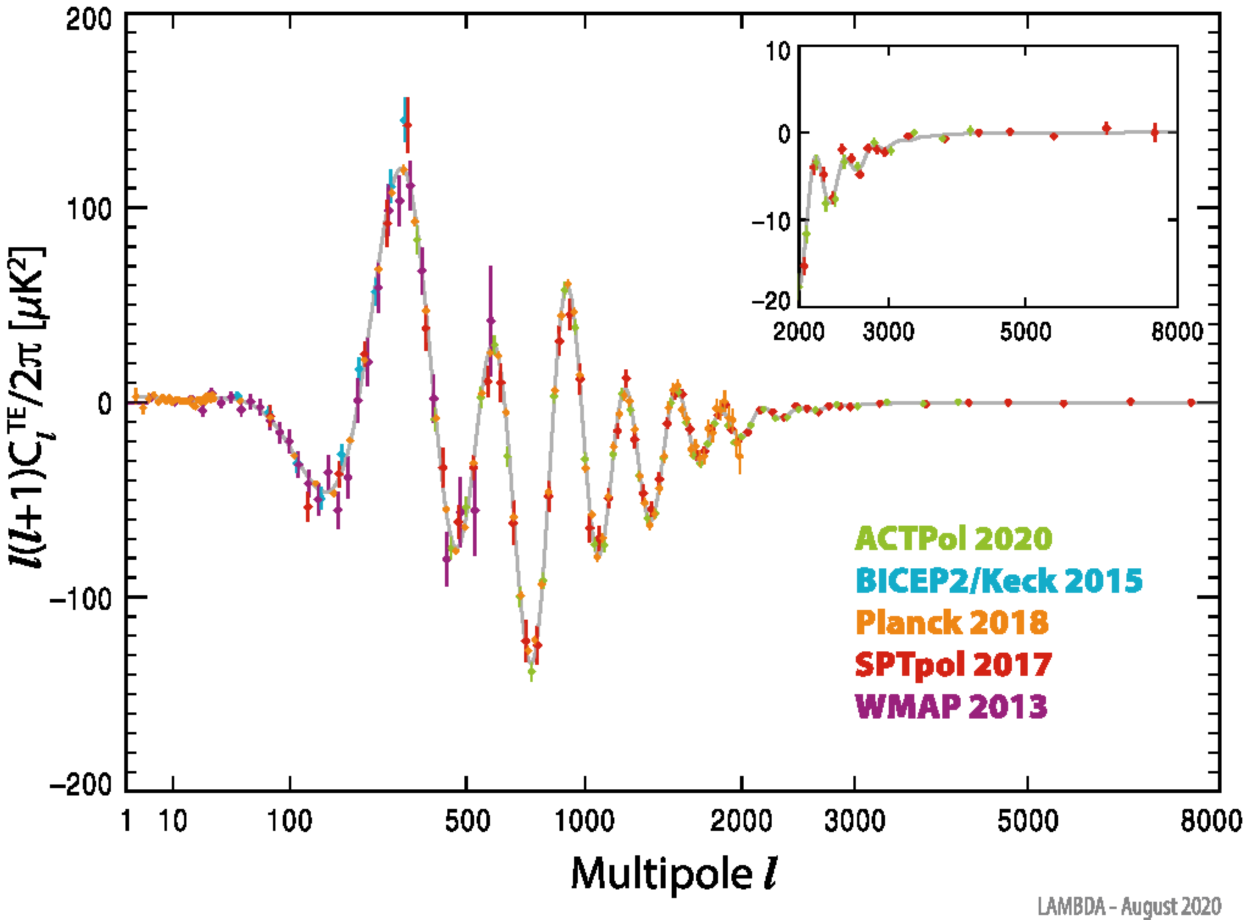


Planck's smoothed temperature map overlaid with polarization data. Warmer spots are redder while cooler spots are bluer, and the black lines represent polarization. Image from the ESA/Planck Collaboration.

In these images, we can see the drastic improvement in the resolution capabilities of our CMB experiments from COBE's time to Planck's time, and CMB experiments have only become more sensitive and precise since then. In the polarization maps, we notice a strong correlation between temperature and (E-mode) polarization anisotropies in the CMB—polarization changes from radial to tangential around cold spots and from tangential to radial around warm spots in the CMB [14]. Recall that the BAO theory for the creation of density fluctuations in the CMB is based on the premise that photons and subatomic particles moved and interacted together in the early universe. Thus, the clear relationship between temperature and E-modes is likely evidence for the BAO theory. The locations of the anisotropies on the sky maps can also help us determine the locations and characteristics of BAOs and the primordial quantum fluctuations that they arose from.

2.3.2. Power spectra

Below is the cross-correlation between the temperature and E-mode power spectra (called the TE power spectrum) of several important CMB experiments:



TE power spectrum from several important CMB experiments. Image from NASA's GSFC.

Analysis of this cross-correlation graph indicates that peaks in the temperature power spectrum occur at the same multipoles as troughs in the E-mode power spectrum [15], which also suggests a direct relationship between density fluctuations and Thomson scattering-induced polarization. Thus, the TE cross-correlation further supports the BAO theory.

2.4. LCDM COSMOLOGICAL PARAMETERS

As we will explain in following sections, the information we can extract from CMB temperature and polarization can be used to calculate several cosmological parameters. These parameters include the current density of baryonic matter ($\Omega_B h^2$); the current density of cold dark matter ($\Omega_C h^2$); the current density of dark energy (Ω_Λ); the Hubble constant (H_0); the age of the universe; the scalar spectral index (n_s) of primordial density disturbances, or how the size of CMB density fluctuations varied with angular scale; the amplitude of curvature fluctuations in the universe ($10^9 \Delta_R{}^2$); total neutrino mass (Σm_v); and how much the CMB has redshifted since reionization (when the first stars and galaxies formed), which tells us how long ago reionization occurred [16]. The Lambda-Cold Dark Matter (LCDM) model of the Big Bang—which states that the modern universe is mainly composed of dark energy, cold dark matter, and baryonic matter, consistent with our observations—predicts particular values for these cosmological parameters [16]. Thus, if CMB data yields values for these parameters that are similar to the LCDM predictions, it would provide strong support for the LCDM model.

3. CMB EXPERIMENTS

To reiterate, analyzing angular temperature and polarization power spectra of the CMB can give us insight into the the density/distribution of baryonic and dark matter in the early universe, the existence of dark energy, the flatness of the universe, inflationary gravitational waves, and what the origins of anisotropies in the CMB are [12]. We will now discuss various experiments intended to measure the temperature and polarization of the CMB in different regions of the sky and how their unique technological designs allowed them to make more precise measurements or reveal a wider range of information than their predecessors.

All the space-based experiments included mechanisms for the apparatus to move through space, sometimes even rotating and/or precessing, in order to scan large portions of the CMB sky, and the scan strategies were designed to ensure that the telescope would never point at the sun and to minimize foreground contamination of the measured signal. To keep the telescopes and detectors as sensitive as possible, all the experiments also had cryogenic cooling systems for their instruments. There is also consistently a dipole anisotropy in all CMB data because of Doppler shifts caused by the Earth's motion relative to the sun [17]; the experiments all use a specific algorithm to eliminate the effect of this anisotropy, with minimizing systematic errors in general being a top priority of all CMB experiments.

3.1. COBE

Experimental Design:

COBE was the first probe designed to measure the CMB. It consisted of 3 main instruments with unique functions: The Differential Microwave Radiometer (DMR), which mapped CMB anisotropies based on scan data; the Far Infrrared Absolute Spectrophotometer (FIRAS), which compared the CMB power vs. radiation frequency spectrum to a blackbody spectrum; and the Diffuse Infrared Background Experiment (DIRBE), which looked for infrared radiation in the CMB--radiation also known as the Cosmic Infrared Background [18]. For the purposes of this paper, we will only focus on the first 2 instruments. The DMR utilized a pair of horn antennas separated by 60º, each measuring 3.5º of the sky [19]--a very large angular scale. Alternating between receiving input from each individual antenna, the DMR measured the difference in CMB temperature in the 2 distinct locations observed by the antenna, later integrating this information into a sky map with hot and cold spots. The DMR has 2 receivers measuring at 3 frequencies: 31.5 GHz, 53 GHz, and 90 GHz [20]. This wide range of frequencies allowed for more precise elimination of foreground signals produced by emissions from intragalactic electrons and dust from the data [19]. Analysis of the Earth motion-produced dipole anisotropy in DMR data, relevant signal-to-noise ratios, and galactic foreground emissions confirm that the features detected by the DMR were actually from the CMB and not some kind of external noise [19], and that systematic errors in the DMR data collection were not that significant.

Science Conclusions:

DMR measurements aligned with simulation-based predictions for CMB behavior, including that CMB temperature anisotropies are random and exist at all angular resolutions [21]. DMR measured the average temperature of the CMB to be 2.725 ± 0.02 K [21], and analysis of the temperature fluctuation angular power spectrum created from DMR data revealed that temperature anisotropies were in fact caused by density fluctuations in the early universe that were originally sourced from primordial quantum fluctuations [21]. FIRAS first created a power vs. frequency spectrum of the DMR temperature data, then compared it with that of a blackbody. The 2 spectra matched almost perfectly, confirming the CMB's blackbody behavior. FIRAS also further constrained COBE's estimate of the CMB's average temperature to 2.728 ± 0.002 K [21].

3.2. WMAP

Instrument Design:

With such high accuracy, especially for the first direct measurements of the CMB ever made, the main limitation of COBE was that it scanned such wide portions of the sky at a time and therefore had very low angular resolution. COBE's successor, WMAP, significantly improved on this issue by scanning only 0.3º of the sky at a time [22]—33 times the angular resolution of COBE [23]. WMAP also used a differential microwave radiometer like COBE, measuring the difference in the temperature of the 2 locations it simultaneously scanned, but it consisted of 2 back-to-back, symmetrical Gregorian telescopes that were 140° apart [24] instead of antenna.

The telescopes had elliptical apertures with a 1.6m major axis and a 1.4m minor axis, and the receivers measure in 5 frequency bands from 22 to 90 GHz (a balance between minimizing atmospheric emission and minimizing dust emission that interfere with CMB signals) with a total of 10 feeds [22]. WMAP was equipped with more feeds for higher frequencies because inherent noise is more prevalent at these frequencies. The receivers also measure the polarization of the signals observed by the telescope in order to differentiate between CMB signals and foreground signals (polarization due to scalar perturbations has a very unique Fourier transform signal) and to create a CMB polarization angular power spectrum. WMAP is also designed with cooling radiators on each side of its primary telescope mirrors and a warm portion inside the Receiver Box to amplify the measured signal, thus increasing WMAP's sensitivity [22] and stability. WMAP used an iterative algorithm to create sky maps and angular power spectra, which means it determined the temperature of a particular location in the sky using the temperature difference measured by the differential microwave radiometer and previous measurements of the temperature of the "opposite" location. Over a 2 year period, WMAP scanned the entire sky multiple times, refining its iterative sky maps with each scan.

Science Conclusions:

WMAP data show that the total energy density of the universe cannot be concentrated in matter and that the universe's radius of curvature is very high, which supports a flat universe and a cosmological constant model for dark energy. Cross-correlations of WMAP-produced temperature and polarization power spectra show that the matter-photon ratio is uniform throughout the CMB, which indicates that BAOs were mostly adiabatic—the photons (radiation) in each oscillation were overdense or underdense by the same factor as the matter in that oscillation. These cross-correlations also indicated a redshift to reionization of about z = 10, confirming that a period of reionization did actually occur in the past (z = 0 is the present day) and that there was not much warm dark matter [25].

However, the calculated z value shows that reionization occurred earlier than previously thought [26], which implies that fast-moving neutrinos didn't significantly contribute to structure formation in the early universe, as these neutrinos would have prevented the formation of overdensities in the primordial photon-baryon plasma and thus delayed structure formation. Some of the main cosmological parameter values and extensions calculated from the final round of WMAP data (alone, not combined with any other data sets) are as follows:

Parameter	Nine-year
Fit parameters	
$\Omega_b h^2$	0.02264 ± 0.00050
$\Omega_c h^2$	0.1138 ± 0.0045
Ω_Λ	0.721 ± 0.025
$10^9 \Delta^2_{\mathcal{R}}$	2.41 ± 0.10
n_s	0.972 ± 0.013
τ	0.089 ± 0.014
Derived parameters	
t_0 (Gyr)	13.74 ± 0.11
H_0 (km/s/Mpc)	70.0 ± 2.2
σ_8	0.821 ± 0.023
Ω_b	0.0463 ± 0.0024
Ω_c	0.233 ± 0.023
$z_{\rm reion}$	10.6 ± 1.1

Hinshaw, G. et. al., NINE-YEAR WILKINSON MICROWAVE ANISOTROPY PROBE (WMAP) OBSERVATIONS: COSMOLOGICAL PARAMETER RESULTS, 2013.

After combining WMAP data with the latest data on Type Ia supernovae and removing systematic errors, scientists have determined a more precise value of 73.8 ± 2.4 km/s Mp/c for the Hubble constant [25]. The measurement of the redshift to reionization suggests that reionization occurred when the universe was between 200 million and 400 million years old.

WMAP data also offers evidence for the Big Bang Nucleosynthesis model, refuting "cold Big Bang" models with its constraints on the amount of helium and effective number of relativistic particle species in the early universe. WMAP data also imposed tighter constraints on neutrino masses and parity violations. Recall that neutrinos counteract matter clumping; thus, studying matter overdensities in the early universe reveals limits on the amount of neutrinos present in the early universe [14].

Importantly, the anticorrelation of CMB temperature and polarization and value for the scalar spectral index indicated by WMAP data rule out several models of inflation [27]. However, WMAP was unable to detect any signatures of inflationary gravitational waves in CMB polarization, which would have guaranteed the existence of an inflationary epoch. Thus, a major goal of many CMB experiments after WMAP was/is to measure and create a gravitational wave power spectrum, as the constraints on primordial GW imposed by WMAP do not eliminate many models of inflation [27].

3.3. PLANCK

Instrument Design:

WMAP's most prominent successor was Planck. Planck consisted of an off-axis Gregorian telescope with an effective aperture of diameter 1.5 m and 2 radio detectors that measured the temperature of the CMB in the location observed by the telescope: The Low Frequency Instrument (LFI), which measures in frequencies between 27 and 77 GHz, and the High Frequency Instrument (HFI), which measures from 83 GHz to 1 THz [28].

The LFI is made up of high electron mobility transistor mixers that amplify signals picked up by the telescope so that their temperature can be measured by a square-law detector diode. The phase of the LFI changes as Planck continues its orbit and the front end of the instrument is equipped with second hybrids, which eliminates the need for phase-preserving waveguides during processing and thus makes Planck data easier to process and less susceptible to errors during analysis than previous experiments' data [29].

On the other hand, the HFI is equipped with 52 bolometers arranged in a spiderweb pattern with a thermistor in the center. The outer pieces of the bolometer "spiderweb" are made of silicon nitride; they absorb incident light from the telescope and direct it to the thermistor, which is made of neutron transmutation doped germanium and is therefore very sensitive to changes in temperature.

Once about 100 of the absorbed photons reach the thermistor, the temperature of the thermistor will increase enough to generate an electrical signal. The specific spiderweb pattern is also advantageous: Due to its small size/area, the bolometer is less susceptible to cosmic ray interference and noise from intrinsic instrument vibrations, and it can map rather quickly instead of "staring" at 1 location for longer period of time because it needs less incident light to detect a change in temperature. The HFI measures in frequency bands centered at 100, 143, 217, 353, 545 and 857 GHz, with the 4 lowest bands measuring polarization as well; with more frequency bands at higher frequencies than WMAP, the HFI can more precisely separate CMB signals from foreground signals [30].

Science Conclusions:

Overall, Planck's design makes it 10 times more sensitive and gives it 50 times better angular resolution than COBE. The cosmological parameter values determined from Planck measurements are shown below:

Parameter	*Planck* alone
$\Omega_b h^2$	0.02237 ± 0.00015
$\Omega_c h^2$	0.1200 ± 0.0012
$100\theta_{MC}$	1.04092 ± 0.00031
τ	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.044 ± 0.014
n_s	0.9649 ± 0.0042

H_0	67.36 ± 0.54
Ω_Λ	0.6847 ± 0.0073
Ω_m	0.3153 ± 0.0073
$\Omega_m h^2$	0.1430 ± 0.0011
$\Omega_m h^3$	0.09633 ± 0.00030
σ_8	0.8111 ± 0.0060
$\sigma_8(\Omega_m/0.3)^{0.5}$ . . .	0.832 ± 0.013
z_{re}	7.67 ± 0.73
Age[Gyr]	13.797 ± 0.023
r_*[Mpc]	144.43 ± 0.26
$100\theta_*$	1.04110 ± 0.00031
r_{drag}[Mpc]	147.09 ± 0.26
z_{eq}	3402 ± 26
$k_{eq}[\mathrm{Mpc}^{-1}]$	0.010384 ± 0.000081
Ω_K	-0.0096 ± 0.0061
Σm_ν [eV]	< 0.241
N_{eff}	$2.89^{+0.36}_{-0.38}$
$r_{0.002}$	< 0.101

Aghanim, N. et. al., Planck 2018 results. I. Cosmological parameters, 2019, arXiv:1807.06205.

As seen in this data table, the Planck-measured value for the Hubble constant is significantly different from the WMAP-measured value. Planck scientists trusted that future experiments would resolve this discrepancy, but to this day, there is no clear consistency between Hubble constant values measured by different experiments. This problem is called the Hubble tension and continues to be an important area of investigation in physics. That said, Planck data is otherwise generally consistent with WMAP data and the LCDM and BAO models. In Planck's sky maps and power spectra, there is a clear correlation between temperature and polarization, with E-modes observed to surround hot spots in the CMB; this provides strong support for the acoustic oscillation theory [31]. Planck data allowed scientists to constrain 5 out of 6 LCDM parameters to be accurate to within 1% and verify that dark energy only recently became the dominant component of the universe [31].

The baryon density inferred based on acoustic oscillation data is consistent with the Big Bang Nucleosynthesis model, and the universe was confirmed to be flat. Planck was the first

CMB experiment to create a gravitational lensing power spectrum and account for this lensing while calculating cosmological parameters. It was this analysis that found that gravitational lensing smooths curves on the CMB temperature power spectrum and changes some E-modes into B-modes; lensing was also found to give insight into early stages of the universe [31], helping further constrain cosmological parameters.

Along with Planck's temperature power spectrum's peaks, which stem from differences in gravitational potentials in the early universe, Planck data on gravitational lensing support LCDM models of general relativity in the early universe [32]. Planck's power spectra also show an amplification of E-modes at low multipoles, which suggests that a period of reionization did occur, Planck data also strongly support the gravitational instability model for structure formation, the theory that CMB anisotropies were the roots of all structure in the universe.

The Planck temperature power spectrum displays faint anomalies on large angular scales, around 5°. These anomalies were much stronger than anomalies in previous measurements and are inconsistent with the LCDM model, raising the question of whether "new physics" may be needed to fully explain CMB behavior. In order to determine whether these anomalies were in fact a sign of new physics or just statistical flukes, scientists compared the temperature data to polarization data. Finding no strong signs of anomalies in polarization, scientists concluded that new physics may be possible but imposed strong constraints on this possibility—for example, the anomalies may be caused by a phenomenon that affects only temperature [33]. The next step in investigating these discrepancies would be to design an experiment that exclusively measures polarization.

3.3.1. Planck x BICEP

Planck also placed an upper limit on inflationary gravitational waves. In 2014, the BICEP & Keck experiments detected B-mode polarization in the sky on large scales, and scientists concluded that they had discovered inflationary gravitational waves. However, because it was in space and was able to measure at higher frequencies than BICEP & Keck, Planck was able to more precisely separate CMB signals from foreground signals and revealed that the B-modes detected by BICEP & Keck were most likely sourced from interstellar dust; more specifically, Planck found that inflationary gravitational waves could not have created more B-modes than half the signal detected by BICEP & Keck [34].

However, Planck measurements do support widely accepted predictions for the overall characteristics of inflation: The cosmological parameters and extensions and BAO data measured by Planck confirm that inflation must have created "a spatially flat universe with a nearly scale-invariant (red) spectrum of density perturbations, which is almost a power law, dominated by scalar perturbations, which are Gaussian and adiabatic, with negligible topological defects." Planck's sky maps show that primary anisotropies follow a Gaussian distribution, which supports the simplest models of inflation with scalar modes and constrains many other models [31].

Planck's polarization measurements have also been used to measure the Sunyaev-Zeldovich effect and the kinetic Sunyaev-Zeldovich effect, when the peculiar velocities of particles encountered by CMB photons change the temperature of these photons. Analysis of these phenomena has revealed further constraints on cosmological parameters and kinetic Sunyaev-Zeldovich dipoles, which has in turn revealed that the LCDM model's limit on large-scale inhomogeneity in the universe is the true upper limit of this inhomogeneity and has thus limited inhomogeneous cosmological models that attempt to explain cosmic acceleration [31].

3.4. ACTPol

Instrument Design:

The cosmological predictions and parameter constraints derived from Planck data would be built on and made more accurate by the ground-based Atacama Cosmology Telescope's polarization experiment (ACTPol), which achieves better angular resolution than Planck by measuring at sub-millimeter wavelengths and, as the name suggests, are especially sensitive to polarization [35].

ACTPol is made up of an off-axis Gregorian telescope with a 6m primary mirror and 3 detector arrays that each correspond to 1° patches in the sky. Two of the arrays (called PA1 and PA2) are identical, measuring in a frequency band centered at 148 GHz (where the CMB signal peaks); the third array (called PA3) simultaneously operates in 2 frequency bands centered on 97 GHz and 148 GHz. At 148 GHz, interference from atmospheric water and oxygen is minimized without compromising high angular resolution or sensitivity to Sunyaev-Zeldovich and CMB signals, leading to the choice of this particular central frequency for ACTPol. Lower frequencies have less atmospheric noise but are more difficult to measure at high angular resolution, while higher frequencies are easier to measure at high resolution but have more atmospheric noise [35]. In general, space-based experiments can measure at higher frequencies because they are not subject to atmospheric interference, which allows them to characterize CMB vs. foreground dust signals more precisely. Thus, ground-based experiments like ACTPol increase their sensitivity by maximizing their detector count, as illustrated by the following examples.

Each of ACTPol's detector arrays is made up of 3 hexagonal and 3 semihexagonal detector wafers and are corrugated with circular silicon platelets—these corrugations allow for low sidelobes, low cross-polarization, and wide-band sensitivity but are easier to make than traditional corrugated feedhorns with the same advantages [35]. Light captured by the telescope is directed to the correct detector arrays with the aid of cryogenic optic tubes that help maximize beam focus onto the detectors. On the way, orthomode transducers also split the light into E- and B-modes depending on its Stokes parameters [9]. Once the light reaches the detectors, transition-edge sensor (TES) bolometers measure and log its temperature. Altogether, ACTPol has 1279 feedhorns and 3068 detectors [35]. The telescope also contains a Lyot stop, an infrared radiation-removing filter as well as several low-pass filters, and metamaterial anti-reflection coatings on many of its parts to minimize contamination of input signals of the CMB and make ACTPol measurements as accurate as possible [35].

Science Conclusions:

The cosmological parameters yielded by ACTPol were largely consistent with those yielded by Planck and support the LCDM model, especially when applied jointly with other experiments' data sets as seen below:

Parameter	ACT	**ACT+WMAP**	ACT+WMAP best-fit	ACT+Planck	Planck
Basic:					
$100\Omega_b h^2$	2.153 ± 0.030	$\mathbf{2.239 \pm 0.021}$	2.223	2.237 ± 0.013	2.241 ± 0.015
$100\Omega_c h^2$	11.78 ± 0.38	$\mathbf{12.00 \pm 0.26}$	12.12	11.97 ± 0.13	11.97 ± 0.14
$10^4\theta_{\rm MC}$	104.225 ± 0.071	$\mathbf{104.170 \pm 0.067}$	104.180	104.110 ± 0.029	104.094 ± 0.031
τ	0.065 ± 0.014	$\mathbf{0.061 \pm 0.012}$	0.061	0.072 ± 0.012	0.076 ± 0.013
n_s	1.008 ± 0.015	$\mathbf{0.9729 \pm 0.0061}$	0.9714	0.9691 ± 0.0041	0.9668 ± 0.0044
$\ln(10^{10}A_s)$	3.050 ± 0.030	$\mathbf{3.064 \pm 0.024}$	3.068	3.086 ± 0.024	3.087 ± 0.026
Nuisance:					
y_p	1.0008 ± 0.0047	$\mathbf{1.0033 \pm 0.0042}$	1.0028	1.0019 ± 0.0046	$- -$
Derived:					
H_0 [km/s/Mpc]	67.9 ± 1.5	$\mathbf{67.6 \pm 1.1}$	67.1	67.53 ± 0.56	67.51 ± 0.61
σ_8	0.824 ± 0.016	$\mathbf{0.822 \pm 0.012}$	0.828	0.8287 ± 0.0099	0.8279 ± 0.011
Additional derived^c:					
Ω_Λ	0.696 ± 0.022	$\mathbf{0.687 \pm 0.016}$	0.680	0.6871 ± 0.0078	0.6867 ± 0.0084
t_0	13.832 ± 0.047	$\mathbf{13.772 \pm 0.039}$	13.786	13.791 ± 0.021	13.791 ± 0.025
S_8	0.830 ± 0.043	$\mathbf{0.840 \pm 0.030}$	0.855	0.846 ± 0.016	0.846 ± 0.017
$10^4\theta^*$	104.252 ± 0.071	$\mathbf{104.189 \pm 0.067}$	104.199	104.128 ± 0.029	104.112 ± 0.031
$D^*_{\rm A}$	13.972 ± 0.091	$\mathbf{13.860 \pm 0.058}$	13.839	13.879 ± 0.027	13.878 ± 0.028
$r_{\rm drag}$	148.6 ± 1.0	$\mathbf{147.06 \pm 0.63}$	146.89	147.18 ± 0.29	147.14 ± 0.30

Simone, A. et. al, THE ATACAMA COSMOLOGY TELESCOPE: DR4 MAPS AND COSMOLOGICAL PARAMETERS, 2020, arXiv:2007.07288v2.

One of the most important results of ACTPol was the 9400 square degree gravitational lensing map it created based on its mass map [36]. This thorough lensing data enabled scientists to constrain $\Sigma m_{Neutrinos}$ to be less than 0.12 eV and the spatial curvature density of the universe to between −0.017 and 0.012, providing even more support for a flat universe. ACT's estimate of the universe's dark energy density is also quite consistent with previous estimates and our observations [36]. Comparing the amplitude of CMB anisotropies measured by ACTPol to the amplitude of matter fluctuations in more modern times based on ACTPol's gravitational lensing data, scientists calculated an optical depth to reionization of $\tau = 0.069 \pm 0.012$, which is consistent with the τ value of 0.0572 ± 0.006 calculated from low-polarization analysis of SRoll2 data [36].

In addition to confirming and further constraining previously measured cosmological data, ACTPol was the first major CMB experiment to investigate the possibility of cosmic birefringence, or the rotation of linear CMB polarization due to external sources, taking advantage of its maximized sensitivity to CMB polarization. The BB and EB power spectra produced by ACTPol showed that the average rotation angle of CMB polarization is very small, suggesting that cosmic birefriengence is unlikely [37], but the existence of this phenomenon has not been fully ruled out and continues to be a topic of investigation.

3.5. SPT-3G

Instrument Design:

After ACT, a top priority for cosmologists was to improve gravitational lensing maps and mass maps; this way, they could study galaxy clustering in more detail and subsequently impose more constraints on cosmological parameters. More precise BAO data derived from these maps would also help refine the neutrino mass measurement, studying very high and very low frequency emissions registered in the mass map would help separate foreground signals from CMB signals for future experiments. The ground-based South Pole Telescope's 3G experiment (SPT-3G) was designed to cater to exactly these goals.

Similar to many of its predecessors, SPT-3G also measured CMB light using an off-axis Gregorian telescope with a 10m-diameter primary mirror. The secondary and tertiary mirrors of the telescope and the receivers are placed on an optical bench so that the incoming light can be focused better, and the telescope measures in 1.12, 1.75, and 2.62 arcminute-sized pixels to achieve high resolution and high quality images. Light travels to the receivers from the telescope through a 685mm diameter window made of high-density polyethylene (HDPE), which has an anti-reflection coating with triangular grooves to damp birefriengence & cross-polarization [38].

Throughout the instrument, Eccosorb HR-10, baffle rings, and other anti-reflection substances/devices and light filters are used to minimize the amount of stray light that can interfere with the detectors. SPT-3G measures in frequency bands centered at 95, 150, and 220 GHz, with a 1.2 arcmin full width and half-maximum beam response at 150 GHz. The instrument consists of 10 detector wafers that each have 269 tri-chroic pixels and hemispherical alumina lenses that couple incoming light to polarization-measuring sinuous antennas. From the antenna, the light then travels through a niobium microstrip to TES bolometers that measure the temperature; because each bolometer corresponds to a particular frequency band, band filters on the microstrip itself split incoming light according to frequency and direct this light to the correct bolometers. Sinuous antennas were chosen in particular because they can measure dual-linear polarization, and their planar geometry makes them less susceptible to cross-polarization. SPT-3G has about 16,000 detectors total, making it the most sensitive CMB experiment thus far [38].

Science Conclusions:

Although SPT-3G is scheduled to continue collecting data until 2024, scientists have drawn several important conclusions from the data the experiment collected from its launch until 2018. The cosmological parameters derived from this data set are overall in agreement with parameters from previous experiments and with the LCDM model, and a number of these parameters have been recalculated using joint constraints from SPT-3G and prior experiments:

	A_L		N_{eff}		$N_{eff} + Y_P$	
	SPT-3G 2018	SPT-3G 2018 + *Planck*	SPT-3G 2018	SPT-3G 2018 + *Planck*	SPT-3G 2018	SPT-3G 2018 + *Planck*
$\Omega_b h^2$	0.02213 ± 0.00033	0.02243 ± 0.00015	0.02254 ± 0.00046	0.02229 ± 0.00020	0.02235 ± 0.00050	0.02228 ± 0.00020
$\Omega_c h^2$	0.1222 ± 0.0060	0.1190 ± 0.0014	0.1235 ± 0.0089	0.1194 ± 0.0028	0.139 ± 0.018	0.1208 ± 0.0042
$100\theta_{MC}$	1.03982 ± 0.00081	1.04087 ± 0.00029	1.03980 ± 0.00092	1.04083 ± 0.00039	1.0359 ± 0.0030	1.0404 ± 0.0011
$10^9 A_s e^{-2\tau}$	1.905 ± 0.041	1.879 ± 0.011	1.886 ± 0.037	1.881 ± 0.016	1.918 ± 0.046	1.884 ± 0.017
n_s	0.956 ± 0.020	0.9677 ± 0.0043	1.001 ± 0.040	0.9628 ± 0.0084	0.985 ± 0.043	0.9630 ± 0.0080
A_L	0.87 ± 0.11	1.078 ± 0.054	–	–	–	–
N_{eff}	–	–	3.55 ± 0.58	3.00 ± 0.18	4.7 ± 1.3	3.09 ± 0.28
Y_P	–	–	–	–	0.165 ± 0.058	0.238 ± 0.016
H_0 [km s^{-1} Mpc^{-1}]	66.1 ± 2.3	67.73 ± 0.64	71.7 ± 4.3	66.9 ± 1.4	77.5 ± 7.2	67.4 ± 1.7
σ_8	0.819 ± 0.023	0.8031 ± 0.0085	0.817 ± 0.029	0.807 ± 0.010	0.831 ± 0.035	0.810 ± 0.012
$S_8 \equiv \sigma_8 \sqrt{\Omega_m/0.3}$	0.864 ± 0.071	0.816 ± 0.018	0.799 ± 0.043	0.831 ± 0.015	0.791 ± 0.043	0.832 ± 0.015
Ω_Λ	0.666 ± 0.037	0.6901 ± 0.0087	0.713 ± 0.026	0.6821 ± 0.0098	0.727 ± 0.029	0.6832 ± 0.0098
Age/Gyr	13.861 ± 0.058	13.789 ± 0.024	13.36 ± 0.54	13.86 ± 0.19	12.59 ± 0.89	13.78 ± 0.25

Balkenhol, L. et. al., A Measurement of the CMB Temperature Power Spectrum and Constraints on Cosmology from the SPT-3G 2018 T T/TE/EE Data Set, 2023, arXiv:2212.05642v3.

The main discrepancy between SPT-3G data and data from previous experiments lies in the Hubble constant value. While some inconsistency is always expected due to the Hubble tension, SPT-3G's measurement of the Hubble constant significantly intensifies the Hubble tension because it is far below the most precise estimate of the Hubble tension derived through supernovae and distance ladder methods [39]. Scientists hope that SPT's final data release in 2024 will provide more information on how this problem can be resolved. Additionally, the data display a preference for an n_s value less than 1, which suggests that inflation was flat and did not have a large and positive gradient [39]. Moreover, the data indicate that the factor b, which represents how much baryon clumping in the early universe was driven by magnetic fields rather than by gravity, is less than 0.37 [39]. A b value of 0 indicates no primordial magnetic fields, while a nonzero b value means recombination occurred earlier in the universe's history and we should calculate higher Hubble constants. However, we cannot attribute the Hubble tension to primordial magnetic fields because SPT-3G's precedented precision means there is high confidence in its measurement of b; thus, it is possible that b = 0 and there were no magnetic fields in the early universe [39]. SPT-3G is anticipated to be able to give insight into relativistic particles in the early universe that can potentially help resolve the Hubble tension, galaxy clustering at high redshifts (early periods in the universe's history), tighter constraints on inflation and primordial magnetic fields, and more by its 2024 data release [40]. Specifically, SPT-3G's high resolution enables it to more accurately probe these aspects of the early universe from its measurements of CMB temperature, polarization, and lensing than its predecessors.

3.6. Simons Observatory

The most recent and technically advanced CMB experiment is the Simons Observatory (SO), which is also ground-based and still in the process of deployment in the Atacama Desert. SO's primary purpose is to make the most precise measurements of temperature and polarization to date, measuring in several frequency bands across several angular scales, in order to further constrain cosmological parameters; other objectives include measuring the Sunyaev-Zeldovich effect to detect high-redshift galaxy clusters (the earliest galaxy clusters) and studying how the density and velocity of matter in the universe changed over time. SO consists of a crossed Dragone-design telescope with a 6m aperture, called the Large Aperture Telescope (LAT), and 3 additional telescopes with 42cm apertures, called Small Aperture Telescopes (SATs). The significant size difference between the 2 apertures allows SO to observe at a wide range of angular scale sizes, from 1 arcminute to tens of degrees [41].

SO also observes in 3 frequency band pairs—27 and 39 GHz (LF), 90 and 150 GHz (MF), and 220 and 270 GHz (UHF)—to more precisely observe where the CMB signal peaks and filter out foreground polarization signals. With a field of view of 7.2° and measuring at the MF bands, the LAT is planned to be initially deployed with 7 optical tubes containing 3 silicon lenses and 3 detector wafers each. This equates to the LAT being coupled to a total of over 30,000 detectors [41]. The lenses are all coated with metamaterial to minimize interference in the measurements from reflected light, and the LAT's Dragone design gives the telescope a large field of view and preserves the polarization of incoming light as it travels through the telescope, allowing for a more thorough data set and making polarization measurements easier. The SATs each have 3 silicon lenses with metamaterial antireflection coatings and a baffle to control sidelobe response. Located inside the cryogenic receiver array that services them, the SATs each have 7 detector wafers and 35° fields of view, corresponding to a total of over 30,000 detectors like the LAT. There is also a cryogenic half-wave plate that modifies the received polarization signal to curb systematic errors [41].

The detector wafers are 150mm in diameter and are made of silicon, containing lenslet-coupled sinous antennas and horn-coupled orthomode transducers, and each detector pixel has 4 aluminum-manganese compound TES bolometers. This allows the SO instrument to detect E- and B-modes in the received light in each frequency band in addition to the temperature of the light. Learning from previous experiments in which the instruments ended up needing to be cooled more than expected to maintain their sensitivity, SO's cryogenics are also equipped with 2 times as much cooling power as is calculated to be necessary to avoid precision errors [41].

4. ANALYSIS AND CONCLUSION

Comparing the designs and achievements of each CMB experiment described above, we notice that successive experiments tend to improve on their predecessors' accuracy and precision by increasing angular resolution, which can be achieved by using smaller pixel sizes or large aperture telescopes—telescopes collect light more precisely than antenna and a bigger aperture means more light enters the telescope, and thus more features in the sky are illuminated. However, because some large-scale patterns in the CMB also hold cosmological significance, it may be ideal to have both large and small aperture telescopes in the same CMB experiment to measure the CMB on various angular scales, similar to SO. As for the specific type of telescope, while many of the experiments above were able to make high-resolution measurements with off-axis Gregorian telescopes, using a Dragone telescope like SO's LAT may produce more accurate data since there is no longer the concern of the polarization of the collected light being shifted, reducing the experiment's susceptibility to related errors.

On the note of polarization, orthomode transducers and sinuous antenna seem to be the most sensitive and accurate technologies for measuring polarization, being able to measure dual polarization while minimizing cross-polarization and having been used successfully in several of the experiments described above. As for temperature, using TES bolometers to directly measure the temperature of observed CMB patches appears to be the most accurate approach. TES bolometers are currently the most sensitive instruments to measure CMB temperature, and using differential microwave radiometers and iterative methods to create temperature sky maps (as was done with WMAP) involves the risk of carrying over potential undetected errors from the original data that the maps are based on (data from COBE in the case of WMAP).

The 3 space-based CMB experiments discussed in this paper—COBE, WMAP, and Planck—each had more frequency bands at higher frequencies than their predecessors, which enabled them to better separate foreground signals from CMB signals. This, in turn, allowed for easier de-lensing of B-modes created by dust rather than inflationary gravitational waves. However, building self-sustaining observatories and deploying them to space is not easy; thus, the following 3 CMB experiments—ACTPol, SPT-3G, and SO—are all ground-based, and each one achieves greater sensitivity than its predecessor by having more detectors. This highlights that maximizing the number of high frequency bands in space-based CMB experiments and the number of detectors in ground-based CMB experiments will strengthen their accuracy and precision.

Of course, all experiments must contain features to help curb systematic errors like stray light and unwanted reflection of collected light within telescopes, and keeping measuring instruments at cryogenic temperatures is critical to maintaining their sensitivity. As seen in the above described experiments, examples of design features that can serve these purposes include anti-reflection coatings inside telescopes, corrugations on detector wafers, more compact detectors like Planck's HFI's spiderweb bolometers that are less susceptible to being hit by stray light, and exceptionally powerful cryogenic systems like that of SO.

Revisiting the technological designs of the landmark CMB experiments discussed in this paper, we conclude that future CMB experiments should consist of several telescopes with various sized apertures; detectors with orthomode transducers, sinuous antenna, and TES bolometers; high frequency bands; large detector count, at least an order of magnitude more than current experiments; and features to prevent systematic errors such as antireflection coatings and high through-put cryostat technology. Alongside any new innovations in CMB detector technology that may arise, these features will help enhance the precision and accuracy of future CMB experiments, allowing them to more deeply probe the CMB. As a relic of the Big Bang and other key events in the primordial universe, studying the CMB in more detail will revolutionize our understanding of physics and the origins of the universe on a fundamental level, paving the way for us to quantize gravity, discover new relativistic particles, investigate the nature dark energy, and confirm the values of several cosmological parameters.

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