Status of CMB Observations in 2015

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The 2.725 K cosmic microwave background has played a key role in the development of modern cosmology by providing a solid observational foundation for constraining possible theories of what happened at very large redshifts and theoretical speculation reaching back almost to the would-be big bang initial singularity. After recounting some of the lesser known history of this area, I summarize the current observational situation and also discuss some exciting challenges that lie ahead: the search for B modes, the precision mapping of the CMB gravitational lensing potential, and the ultra-precise characterization of the CMB frequency spectrum, which would allow the exploitation of spectral distortions to probe new physics.

1. Introduction

The Cosmic Microwave Background (CMB) is an almost perfect, nearly isotropic blackbody radiation now at a temperature of 2.725 K emanating from the big bang itself. As a practical matter, it is the oldest fossil remnant of the primordial universe available to us for precision characterization. The precise mapping of the CMB anisotropies in both temperature and polarization has allowed us to reconstruct the initial conditions of the universe. As we have learned, these initial conditions are remarkably simpler than one might have imagined. Twenty years ago people wanting to model how the recent universe evolved from initial conditions were forced to insert in their codes initial conditions that were at best tentative guesses, but today we believe that we know what the correct initial conditions were, with uncertainties in the parameters presently at about the few percent level. Today the greatest uncertainty in such studies of how the late universe evolved out of these initial conditions arises from the modeling of the late time physics itself. While the physics

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of the CMB is linear and simple, the late time physics of the universe is nonlinear and complex. Processes — such as gravitational clustering, hydrodynamics, magnetogenesis, MHD, star formation, supernova explosions and their aftermath, to give an incomplete list — must be modeled, either by starting from first principles or in many cases by using more *ad hoc* models and relying on late time observational data to fix the parameters of these phenomenological models. The CMB by contrast offers a relatively clean probe of the state of the universe before nonlinear physics kicked in. Even the quantum field theory that enters into computing the generation of the primordial density during a prior epoch of inflation is conceptually relatively simple: it is, for the most part, free field theory, which some quantum field theorists would regard as classical, because it is tree level, or order $\hbar^0$ in the loop expansion. In other words, one takes the modes of the classical field theory, normalizing them according to classical canonical commutation relations, and one replaces the *c*-number coefficients with annihilation and creation operators, just as for the simple harmonic oscillator. The study in the 1970s and 1980s of semi-classical quantum field theory in a curved spacetime (see for example the book by Birrell and Davies⁴ and references therein) raised some interesting new issues and became one of the principal theoretical tools for the subsequent calculation in the mid-1980s of the perturbations predicted from the leading order quantum corrections to the classical inflationary cosmology.

This program requires some courage. We do not know the correct theory of quantum gravity, but we linearize the classical theory and proceed to quantize this linearized theory making predictions as if we had a theory of quantum gravity. Perhaps one of the virtues of inflationary cosmology as developed in the 1980s is that it protects us from our ignorance. Inflation provides an ingenious mechanism for hiding any clues as to what happened during a possible earlier Planck epoch, presumably governed by strongly coupled gravity at the quantum level, for which we today have hardly any idea as to the character of the underlying theory. To be sure, we have superstring theory, which is very promising at the formal level. But we do not know how to calculate predictions relevant for the very early universe.

Cosmic inflation is an incomplete theory. Some call it the “inflationary paradigm,” but I do not like this term, which alludes to Thomas Kuhn’s “paradigm shifts,” which are momentous and revolutionary discoveries after which science emerges not the same as before. However the older meaning of “paradigm,” referring to Latin grammar, is less glorious. According to Webster’s Third International Dictionary,² a paradigm is “an example of a conjugation or declension showing a word in all its inflectional forms.” Unfortunately, the number of inflationary potentials that have been proposed in the literature is immense. The problem is that the theory does not make a definite prediction for the form of the inflationary potential, so there are, at least technically speaking, almost an infinite number of free parameters, corresponding to a free function. We can, however, make predictions by assuming the absence of ‘features,’ or bumps and dips in the potential. Assuming that the inflationary potential is relatively smooth and well behaved, we can, for

example, expand the inflationary potential as a power series within the observable region where the cosmological perturbations visible to us today were imprinted, and retaining only the first few terms, we obtain approximate predictions. But there is something unsatisfying about the lack of an unambiguous base theory. We can speak of the emergence of a Standard Model of Cosmology, but the analogy to the standard electroweak model of Weinberg and Salam is imperfect. In that case, there are precisely 26 undetermined parameters,^a and when we talk about “Physics beyond the Standard Model,” we know exactly what we are talking about.

For my talk I was asked to provide an overview of the observations of the cosmic microwave background (CMB) including its history, the present state of our knowledge of the CMB, and also some indications about the future of this field with a description of the experiments now in progress or being planned, as well as describing some of the challenges that must be overcome in order to make the observations that we would like to make. This is a broad remit, and what is included here constitutes an arbitrary selection, reflecting my own personal biases. For a more detailed and complete overview, the reader is invited to consult my review article,¹ and in particular the many references cited therein.

2. Pre-History of the CMB

Here I will try to emphasize some lesser known aspects of the story of the CMB, which has become part of the canon of modern cosmology, referring the reader elsewhere for a more complete account.²⁴ The history of the CMB reaches back much earlier than most people realize, with key observations pre-dating the prophetic set of papers around 1948 of which the most cited is Alpher, Bethe, and Gamow,⁵ in which a CMB temperature of approximately 5 K was predicted.^b

The observational evidence for the CMB with a measurement of its temperature already existed in studies of the relative intensities of absorption lines in spectra of nearby hot stars taken at optical frequencies. Although the primary optical transitions are electronic, the electronic levels are split into both vibrational and rotational sublevels. The relative populations of these sublevels can under the right conditions serve as molecular thermometers that can be used to measure the thermodynamic brightness temperature of the radiation field at the frequency corresponding to rotational transitions between the sublevels. In the general case, this procedure does not work, because several competing effects enter into determining the relative level populations (e.g., collisions, excitation by UV photons, etc.), each process being characterized by its own effective temperature. However, to the extent

^aThe 26 standard model parameters are enumerated as follows: 3 gauge couplings, (i.e., g_{color} , $g_{SU(2)}$, and $g_{U(1)}$), 2 Higgs potential coupling constants, 3 charged lepton masses, 6 quark masses, 3 neutrino masses, 4 parameters for the CKM quark mixing matrix and 4 more for the neutrino mixing matrix, and finally θ_{QCD} .

^bFor a nice short account of these early papers leading to our modern understanding of primordial nucleosynthesis, see P.J.E. Peebles, “Discovery of the Hot Big Bang: What happened in 1948,” (arXiv:1310.2146)

that the coupling to the radiation field dominates over other effects, the relative level populations provide an accurate measure of the radiation field temperature.

The three molecules originally studied were the diatomic molecules CN , CH , and CH^+ . The expectation based on laboratory experiments carried out at room temperature was that a whole series of ‘bands’ resulting from rotational-vibrational splittings into sublevels should be visible for all these molecules. But instead only two sublevels were observed for the CN molecule, corresponding to the rotational $J=1-J=0$ splitting of the ground state, and for CH , and CH^+ only a single line was observed, suggesting that all these molecule are in their rotational ground state. The $J=1-J=0$ rotational transitions for the CN , CH , and CH^+ molecules correspond to the frequencies 228 GHz, 535 GHz, and 834 GHz (or the wavelengths 1.32 mm 0.56 mm, and 0.36 mm), respectively. For comparison, the modern value of the CMB temperature converted to a frequency is $\nu_{CMB} = k_B T_{CMB}/h = 57$ GHz. For the CN relative populations, McKellar²⁵ deduced an effective temperature of around 2.1 K; however, he did not go further to analyze the possible consequences of his finding. It was only after the discovery by Penzias and Wilson that the coincidence of their direct microwave temperature measurement with the temperatures recorded using these molecular thermometers was noted. It was then recognized that the CMB could have been discovered earlier if these measurements had been correctly interpreted.

Having described the first observation of the CMB, we now go on to discuss the first theoretical work by Alpher, Bethe, and Gamow (although Bethe’s name was added only to complete the pun). It should be noted that the work by Alpher, Bethe, Gamow, and Hermann received little attention at the time, partially for reasons that in retrospect are not unreasonable. Today ‘primordial nucleosynthesis’ is regarded as one of the ‘observational pillars’ of the hot big bang model, but the observational data needed to arrive deductively at this conclusion did not exist at the time. In 1948 the challenge was to explain the abundances of all the elements seen in the present universe, ranging from hydrogen to iron and beyond, and primordial nucleosynthesis predicted that the baryons in the universe would end up almost exclusively in the form of 1H and 4He , with literally trace amounts of a handful of other light elements 2D , 3He , 7Li , and 7Be . Around 1948 most researchers looked toward processes within stars for producing the heavier elements. They were not aware that stars alone could not account for the entire observed helium abundance and that something more than nuclear burning in stars was required to explain the observed relative isotope abundances.

It is ironic that in the 1990s before the hot big bang cosmology had become thoroughly incorporated into the received wisdom, some critics cited as one of their arguments against the big bang the lack of agreement of the 1948 Alpher, Gamow, and Hermann prediction of a 5 K CMB temperature⁵ with the modern observed value of 2.725 K. Yet if we examine this prediction in light of the knowledge at the time and redo the theoretical analysis more carefully, we arrive at the conclusion that Alpher et al. were lucky not to have been off by an even greater factor. It turns

out that unless one does extremely sensitive measurements, which have been carried out in the meantime, the basic prediction that about a quarter of the baryonic mass is in the form of ${}^4\text{He}$ results over an extremely broad range of values for the input parameter η_B (the baryon-to-photon number density ratio), which is the only adjustable free parameter of primordial nucleosynthesis. At the time, attention was not so much focused on the possibility of primordial nucleosynthesis but more on the nuclear processes in stars, especially for generating the heavier elements. It was not then evident that both primordial and stellar nucleosynthesis were required to explain the current observed relative element abundances.

3. From Penzias and Wilson to COBE

In many accounts in the secondary literature of the discovery of the CMB by Penzias and Wilson in 1965 the word ‘serendipitous’ (not exactly among the most commonly used English words) pops up over and over. While there is some truth in this description, in reality the discovery of the CMB was less accidental than sometimes depicted. The frontiers of electronics and communication have greatly shifted since the mid-1960s. Low noise and high frequency had quite a different meaning then, and the problem Penzias and Wilson had set out to explore was the ultimate limits of noise for communication in the frequency range around 4 GHz. They embarked on the systematic study of this question in an effort spanning many years and exploring many possible sources. The account depicting of Dicke’s Princeton experiment on the verge of discovering the vestiges of the big bang but being scooped by some folks at Bell Labs who did not really know what they were doing does not do justice to the contribution of Penzias and Wilson. At nearly the same time, Robert Dicke and collaborators at Princeton, unaware of the prior work by Gamow and collaborators, had speculated that there should be a CMBR and had constructed an apparatus to measure its signal. However before they could complete their measurement, the news arrived that Penzias and Wilson had detected the signal that they had set out to seek, and the outcome was that two papers were published back to back in the *Astrophysical Journal*, one by Penzias and Wilson, preceded by a paper by Dicke, Peebles, Roll and Wilkinson explaining how this signal could be explained in a hot Big Bang cosmological model.

There is a long gap between the discovery of Penzias and Wilson of the CMB at zeroth order and the discovery of the CMB anisotropy by the COBE DMR in 1992, which was accompanied by what remains to date the best measurement of the CMB frequency spectrum by the COBE FIRAS instrument. This long gap of almost thirty years can be understood largely by the fact that the technology to make the necessary measurements was lacking and not that the importance of looking for anisotropies and deviations from a blackbody spectrum had not been recognized. A detailed history of the pre-COBE experiments searching for a possible anisotropy in the CMB temperature and for deviations from the blackbody form for the frequency spectrum can be found in the reviews by Weiss³⁵ and by Readhead and Lawrence.³⁶

The technical challenges to be overcome to carry out measurements at the required accuracy were formidable, and it took quite some time for the upper limits to reach the level of the actual CMB anisotropy as finally discovered by COBE.

In 1992 the COBE team announced the first discovery of an anisotropy of the cosmic microwave background using the DMR (Differential Microwave Radiometer) instrument.²⁸ The DMR consisted of pairs of horns pointing in directions separated by approximately 60° in the sky. The detectors were rapidly switched between the horns and only the difference in signal was recorded. Through the spinning and precession of the satellite, a data stream consisting of differences in the CMB temperature was recorded at three frequencies and sky maps were constructed using this data. With the data smoothed to 10° , the COBE team found an rms anisotropy of $30 \pm 5 \mu K$ (or $\Delta T/T = 11 \times 10^{-6}$) for the primordial blackbody signal. The shape of the spectrum was found consistent with scale invariance (although with large uncertainties, i.e., $n = 1.1 \pm 0.5$) as predicted by inflationary models. The COBE FIRAS instrument probed the absolute frequency spectrum of the CMB by rapidly switching a Fourier transform spectrometer between the sky and an artificially constructed blackbody source. COBE FIRAS constrained the rms deviations of the CMB from a perfect blackbody to be less than 5 parts in 10^5 over the frequency range 60 – 630 GHz.²⁷

Competing theoretical cosmological models had an undetermined or floating normalization, but when normalized to COBE, a prediction for the normalization of the primordial power spectrum of density fluctuations followed, usually expressed in terms of σ_8 (i.e., the rms fractional mass fluctuation $\delta M/M$ within a sphere of radius $8h^{-1} Mpc$), could be obtained, and this predicted σ_8 could be compared to data from galaxy surveys. Models with adiabatic fluctuations, as produced in the simplest inflationary models, produced higher values of σ_8 than models with isocurvature perturbations or models with structure formation through topological defects.

The next step was to explore how the CMB angular power spectrum extended to smaller angles. A host of ground and balloon based experiments followed on the COBE detection, and it took some time for the observational situation to become clear. For a number of years, a plot summarizing the observational situation showing all the experiments extending the COBE DMR experiment to smaller angular scales somewhat resembled a target where the marksman often altogether missed the target. Theorists could hand pick the points they liked, claiming that based on inside information certain points should be believed more than others. (See for example the figure of Max Tegmark in ref. 34.) The observations improved gradually. It is usually the Boomerang²¹ and Maxima²² experiments that are credited with having provided the first clear and convincing evidence of the acoustic oscillations. The next major step was the WMAP space mission, often described as the “second-generation” CMB space mission, following on COBE.

4. The WMAP and Planck Space Missions

The NASA WMAP satellite was launched in 2001 and delivered its first results in 2003 concerning the CMB temperature anisotropy over the whole sky. WMAP's first CMB polarization results were reported in 2006, and WMAP continued taking data until 2010. Periodic updates of the WMAP results were subsequently published taking into account more data and refining the analysis. Like COBE, WMAP surveyed the entire sky, but because WMAP used a pair of telescopes rather than horns pointing directly at the sky, WMAP had a superior angular resolution. WMAP observed in five frequencies: 23, 33, 41, 61, and 94 GHz. The lowest frequency bands were the most contaminated by Galactic synchrotron radiation, and the highest (or highest two) frequency band was the cleanest. Because of the HEMT detection technology employed, WMAP could not reach higher frequencies where Galactic thermal dust contamination starts to become dominant.

I vividly recall the first press conference when the WMAP collaboration announced their first scientific results, and given that this was the first post-COBE CMB space mission, there were great expectations that some bombshell was going to be dropped. Boomerang²¹ and Maxima²² had presented fairly convincing evidence for the first Doppler peak at precisely the position predicted by Λ CDM combined with simple inflationary models. Even though these observations killed off a lot of models — or at least made most of these models very difficult to defend, the error bars were still quite large, and there remained the possibility that WMAP with its high precision and full sky coverage would conclude “none of the above” for the many still contending theoretical models. As a theorist, this was certainly my hope, because simple models of single scalar field inflation are rather boring. At the press conference, John Bahcall summed up that “the greatest surprise [from WMAP] was that there was no surprise.” Indeed WMAP found that their measured temperature power spectrum was consistent with the simplest six-parameter model. The six parameters were A_S , n_S , H_0 , $\omega_b = h^2\Omega_b$, $\omega_c = h^2\Omega_c$, and τ . Or equivalently, one could use any other six independent parameters derived from these parameters.

One of the interesting novelties from among the WMAP results was the measurement of the spectral index of the power spectrum, which prior to WMAP was consistent with $n_S = 1$, which would be the prediction if there were an exact unbroken scale symmetry. While inflationary potentials can be constructed — or some might say ‘designed’ — through fine tuning to give n_S arbitrarily close to one, generically inflation predicts some deviation from exact scale invariance, most likely but not inexorably on the side $n_S < 1$. The three-year WMAP results in the framework of the previously described six-parameter model measured $n_S = 0.958 \pm 0.016$, thus excluding a scale-invariant primordial power spectrum at approximately 2.6σ . For many this result strengthened the case for inflation, as opposed to some unspecified more symmetric theory for imprinting the primordial cosmological perturbations.

WMAP also was able to place interesting constraints on primordial non-Gaussianity and discovered a few ‘anomalies’ at modest statistical significance,

a topic to which we shall return below in our discussion of Planck. Until the Planck 2013 Cosmology Results were announced, the WMAP characterization of the temperature power spectrum on intermediate scales remained unrivaled, although ground-based experiments, most notably ACT¹⁸ and SPT,¹⁹ succeeded in extending the measurement of C_ℓ^{TT} to smaller scales extending to around $\ell \approx 10^4$.

In these proceedings I shall not dwell on the ESA Planck space mission because Planck has over the last few years released two sets of cosmology results, one in 2013 and another in 2015. These results have been the subject of many plenary conference presentations. It is therefore doubtful that I can in the small number of pages available tell you something that you have not already heard or read elsewhere. For this reason I invite you to consult the relevant 2013 and 2015 papers for a complete account. Let me however give you my own take on the main scientific impact of the Planck.

Planck had the capability to improve on WMAP in several ways owing to its ten times better sensitivity and two times better angular resolution.²⁰ The dimensions of the Planck and WMAP telescopes were roughly comparable, with a usable diameter of slightly over a meter, the main difference between the two missions being the types of detectors deployed. WMAP deployed coherent detectors passively cooled to about 95 K and less sensitive, while Planck used, at least for the six highest HFI (High Frequency Instrument) frequency channels, more sensitive bolometers that were cryogenically cooled to ≈ 100 mK. On a space mission, bolometers are more risky because failure of the cooling system to perform adequately would prevent any useful data from being taken. Bolometers however present two significant advantages: (1) Bolometers function nearly at the limit of the inherent quantum noise of the incident photon flux, whereas the sensitivity of coherent detectors is worse than this fundamental limit by a substantial factor, and (2) coherent detectors for measuring CMB anisotropies are able to operate only up to about 100 GHz, whereas bolometers function successfully at much higher frequencies extending into the Wien tail of the CMB blackbody frequency spectrum. WMAP mapped the microwave sky in five bands centered at 23, 33, 41, 61, and 94 GHz, whereas Planck mapped the sky in nine bands centered at 30, 44, 70, 100, 143, 217, 353, 545, and 857 GHz. The extended reach of Planck thanks to these higher frequency bands allowed measurements where the dust contributes substantially to the sky signal — and even dominates over the CMB in the highest bands, thus allowing better cleaning of nonprimordial contaminants and substantially reducing uncertainties in the possible role of dust contamination in the final cleaned CMB maps. The highest Planck frequency (at 857 GHz) is situated far into the Wien tail of the CMB, so that except very near the galactic poles, one sees hardly any CMB. Almost all the signal comes from thermal dust emission from our Galaxy as well as from infrared galaxies. The presence of these higher frequency channels constitutes an additional advantage. Since CMB measurements are almost always diffraction limited, given the roughly comparable dimensions of the telescopes, Planck benefits from a better angular resolution.

Fig. 1. **Planck 2015 TT Power Spectrum.** The upper subplot shows the binned C_ℓ^{TT} power spectrum (where $D_\ell^{TT} = \ell(\ell+1)C_\ell^{TT}/2\pi$) compared to the best fit six-parameter theoretical model (red), and the lower plot shows a zoom of the residuals. The fit is quite good except for a dip around $\ell \approx 20$, whose statistical significance is around 2σ . (Credit: ESA/ Planck Collaboration)

The temperature power spectrum reported in the Planck 2013 Cosmological Results release was consistent with the same six-parameter model used for the WMAP analysis. Figure 1 shows the temperature power spectrum from the 2015 Cosmology release. (For more details, see Refs. 7 and 6.) One could say that the John Bahcall’s 2001 WMAP summary that the “greatest surprise was that there was no surprise” could equally well be applied to the Planck results, despite the considerable scope to detect anomalies as explained above. The Planck C_ℓ^{TT} power spectrum shows several improvements of a qualitative nature relative to the WMAP C_ℓ^{TT} power spectrum. While only three acoustic oscillations are clearly visible in the WMAP power spectrum before the error bars start to blow up at higher ℓ , the Planck power spectrum shows clearly five acoustic peaks, and moreover the decay of the damping tail is precisely mapped out to about $\ell \approx 2500$ where things start to fall apart. At this point beam smearing combined with the limited sensitivity causes the error bars to almost literally blow up toward higher ℓ , so that beyond $\ell \approx 2500$ there is little useful data.

The other result from 2013 that was perhaps surprising to a lot of theorists was the stringent upper limits established by Planck on the possible primordial non-Gaussianity. In the WMAP data, there were some hints at very modest statistical significance of an $f_{NL} > 0$. Yadav and Wandelt⁸ reported that according to their independent analysis of the WMAP data, $f_{NL} \in [27, 147]$ at 99.5% confidence level

Fig. 2. **Planck polarization power spectra.** The C_ℓ^{EE} (left) and C_ℓ^{TE} (right) power spectra reported in the Planck 2015 release show that the observed polarized anisotropies are broadly consistent with the six-parameter concordance model. The error bars shown should be understood as unreliable and as a lower bound on the actual errors, because as the Planck 2015 papers reported, there remains some evidence of unaccounted or uncorrected systematics in the polarization maps, most notably $T \rightarrow E$ leakage. (Credit: ESA/ Planck Collaboration)

with a central value of $f_{NL} = 87$. Other analyses found somewhat lower values, but despite disagreement on the details, most analyses found a hint of a signal with $f_{NL} > 0$ at low statistical significance. In the wake of these developments, theorists worked feverishly to devise models predicting a large primordial bispectral non-Gaussianity. Many of these theorists expected a Planck confirmation of the hints found by WMAP, but in its 2013 analysis based on the temperature maps, the Planck Collaboration reported $f_{NL} = 2.7 \pm 5.8$, thus laying to rest the hint of a detection that some had seen in the WMAP data. The 2015 Planck results, which additionally included polarization, gave consistent constraints.

The Planck 2015 results also included the CMB C_ℓ^{EE} auto-correlation power spectrum as well as the C_ℓ^{TE} cross-correlation power spectrum. (See Fig. 2.) The polarization of the CMB had first been discovered by DASI in 2002²³ and was later mapped over the whole sky by WMAP at lower resolution and sensitivity than in the 2015 Planck results. The first WMAP polarization results were released in 2005 based on the WMAP 3-year data, and updated using the WMAP 5-year, 7-year, and 9-year data were also released. The Planck polarization power spectrum when analyzed independently without using the temperature data gives cosmological parameters consistent with those obtained using the TT data alone and with those using all the data. This fact indicates that the CMB polarization tells a consistent story, corroborating the story told by the temperature anisotropies alone. The signal-to-noise ratio of the Planck $a_{\ell m}^E$'s hovers near or below unity until about $\ell \approx 1000$, where the error bars start to blow up.

The Planck team also studied the various anomalies found by the WMAP team at modest statistical significance. These include bipolar disorder (or dipole modulation of the power spectrum), alignments of certain low ℓ multipole moments, and the 'cold spot,' all of which are results at low statistical significance, meaning that one is free either to reject them as statistical flukes or take them as interesting hints

of new physics, according to one's personal tastes. Some believed that Planck with its higher frequency channels might make these anomalies go away by showing that they result from underestimated or improperly corrected Galactic dust contamination. This however did not happen. The anomalies seen by WMAP were broadly confirmed by Planck at comparable statistical significance, a result that is not at all surprising because the limiting factor for both experiments was cosmic variance. Unfortunately, future measurements of the CMB temperature cannot hope to shed additional light on this question, because they too will be seeing that same sky and will be limited by exactly the same cosmic variance. There is however room for modest improvement resulting from using polarization, perhaps from the 2017 Planck low ℓ polarization results when these become available.

In early 2015 the Planck Collaboration released its first cosmological results including polarization data. The measurements of the EE polarization power spectrum at $\ell > 30$ is consistent with the 2013 finding using TT alone, and perhaps more importantly, the cosmological parameters found using EE alone tell a story consistent with the TT only results, showing that the measured polarization power spectrum corroborates the story told by TT. In the 2015 cosmology release, however, it was noted that the polarization data contained evidence of residual systematic errors and that the polarization error bars given are not fully trustworthy. Moreover, the low ℓ polarization power spectrum (for $\ell < 30$) had not been released because the analysis was still ongoing. In early 2017 the Planck Collaboration intends to release a new set of results that will, most importantly, provide Planck measurements of the polarization extending all the way down to $\ell = 2$. This data will help pin down the reionization optical depth as well as giving Planck constraints on r from the reionization bump. It is however doubtful that they constraints will be better than the most recent constraints established by BICEP2/Keck array team.

We now turn to discussing the B modes of the CMB polarization, which have received a lot of attention, especially since the March 2015 announcement by the BICEP2 team of the purported discovery of B modes using measurements in just one frequency channel at 150 GHz.¹⁴ Based on CMB polarization measurements in a patch covering only about 2% of the sky chosen for its low level of galactic foregrounds as measured using temperature maps, the BICEP2 team found a B mode amplitude that if entirely primordial would correspond to $r = 0.20^{+0.07}_{-0.05}$ with $r = 0$ disfavored at 7σ . According to the interpretation put forth by the BICEP2 team, an explanation based on Galactic foregrounds could be excluded because of the extremely large magnitude of the observed signal. This claim made the front pages of newspapers around the world and sparked great enthusiasm in the popular science press. BICEP2 claimed to have investigated the predictions of six dust models and to have found that none of these models could account for a dust contamination having such a large magnitude. There was only a slight problem: there was no publicly available data to fix the parameters of these models, a difficulty not sufficiently appreciated by the four BICEP2 PIs. The only data that could settle this question was in the Planck high frequency polarized dust maps (particularly

the polarized maps at 353 and 545 GHz whose signal is almost exclusively thermal dust emission from our Galaxy), but at that time the Planck Collaboration had not publicly released these maps, nor had they yet presented their analysis. In the early summer a paper by Flauger, Spergel, and Hill¹³ appeared arguing that all the data available at that time concerning polarized dust emission implied that all the signal could be attributed to Galactic dust contamination, although a primordial signal could not be ruled out. In September 2015 the Planck Collaboration finally published the results of their polarized dust analysis showing that in fact the polarized dust magnitude measured by Planck (primarily using the 353 GHz channel) in the BICEP2 field was sufficiently high to account for all the signal.¹⁵ Subsequently Planck and BICEP2 agreed to carry out a joint cross-correlation study in order to determine the actual level of dust contamination. The result of this analysis was that the detection, initially claimed at 7σ , went away, and a new upper bound on $r = T/S$ with $r < 0.12$ at 95 % confidence was established.¹⁶ Subsequent work by the BICEP2/Keck Array team incorporating more recent data improved this bound to $r < 0.09$ at a 95 % confidence level.¹⁷

There are at present many ground and balloon based experiments underway, for example ACT, BICEP2/Keck Array, CLASS, EBEX, Piper, Polar Bear/Simons Array, Quijote, QUBIC, Spider, and SPT aiming to improve the upper bounds on r or to make a first detection. We discuss some of the most ambitious of the initiatives in the next two sections.

5. Where We Stand Today

With some risk of oversimplification, the status of the CMB today could be summed up as follows. The Planck space mission together with ground based experiments such as ACT and SPT extending to smaller scales have mapped the CMB temperature anisotropies to reach almost the cosmic variance limit, and at present the frontier of CMB research is the search for primordial B modes that were presumably generated during cosmic inflation, as well as an ultra-precise characterization of the absolute frequency spectrum by improving on COBE FIRAS.

Before going on to discuss the search for B modes, let us nuance this claim somewhat. At low multipole number ℓ , the Planck determination of the temperature power spectrum is limited by cosmic variance — that is, the fact that we can observe only one sky. If we accept the hypothesis that the primordial scalar perturbations were imprinted by an isotropic Gaussian stochastic process, all useful information in the CMB temperature anisotropies can be compressed into the measured power spectrum C_ℓ^{TT} , and even with the most perfect measurement, there always remains a residual rms fractional uncertainty error of $\sqrt{2/(2\ell + 1)}$ in the measurement of each C_ℓ for the underlying isotropic statistical process that generated our random sky map. Even with the best possible measurements, there is a maximum ℓ beyond which very little precise information can be obtained regarding the primordial perturbations given that beyond $\ell \approx 3000$ other effects rapidly kick in and dominate

the sky anisotropy signal. Only measurements of the primordial signal averaged over broad bands and with large fractional error bars can be obtained beyond this approximate threshold.

This transition from a regime at low ℓ where the primordial CMB signal dominates to a regime at high ℓ where the primordial signal becomes a sideshow is quite abrupt for a number of reasons. Most of the foregrounds that dominate on small angular scales have the power spectrum of white noise or of point sources — that is, $C_\ell^{TT} \sim \ell^0$. The primordial CMB temperature power spectrum, by contrast, at low ℓ scales very approximately as ℓ^{-2} (if one ignores the acoustic oscillations) but at higher ℓ falls exponentially due to Silk damping or ‘viscosity.’ Point sources can be masked, but there are unsurmountable limitations to how much contamination can be mitigated by fancy ‘component separation’ techniques because each point source has its own unique frequency spectrum.

The end result, as estimated by Fisher forecasts for future CMB space missions, is that the error bars on the cosmological parameters may shrink each by a factor of approximately 2–3.^c It has been argued that one can do better with measuring the EE polarization power spectrum because despite the fact that the CMB polarization is harder to measure experimentally on account of its smaller absolute magnitude, the non-primordial contaminants have a smaller fractional polarization than the primordial CMB, and thus for polarization the wall at around $\ell \approx 3000$ moves to somewhat higher ℓ .

The preceding comments should not be misinterpreted as implying that exploring the CMB beyond $\ell \gtrsim 3000$ is not of great interest. As the papers from the ACT and SPT collaborations have shown, there is a lot of interesting science to be done by observing the microwave temperature and polarization anisotropy on very small angular scales, but the primary science goals are not the primordial scalar mode power spectrum but rather the science of what are often termed as the “secondary anisotropies.” Gravitational lensing of the CMB is a very interesting (and clean) probe of the inhomogeneities of the distribution of matter lying between ourselves and the last scattering surface at $z \approx 10^3$. In a certain sense, the idea behind these observations is the same as for studies of weak lensing in the optical and infrared bands, where one observes the ellipticities of galaxies after smoothing. The simplest model would be that except for the lensing shear, the ellipticities would be random and uncorrelated, so that after averaging over many galaxies one recovers the lensing field. However intrinsic alignments add extra noise and biases to the reconstructed lensing field maps. A few differences between CMB and other lensing surveys are worth highlighting: (1) The CMB constitutes the most distant

^cWe shall not follow the Dark Energy community, which uses a figure of merit consisting of the volume factor by which the allowed parameter space is shrunk as the result of better data. This is a dangerous accounting practice susceptible to manipulation, because for example a 30% improvement in the error bars in each of, say, 30 parameters of a model can be billed as an improvement by a factor of almost 50,000. But we all know that a 30% improvement in the error bars is always subject to a lot of caveats, subjective choices, and modelling uncertainties.

exploitable source plane, whereas weak lensing of galaxies does not extend as far back in redshift. This means that linear theory is more applicable to interpreting CMB lensing results than to the weak lensing of galaxies. (2) For constructing a lensing map based on the alignments of the ellipticities of galaxies, it is assumed that there are no intrinsic alignments, which would act to bias measurements. CMB lensing is free of this complication and can be used by studying cross correlations to test for and characterize such intrinsic alignments. Moreover, combining with CMB lensing also provides more powerful ‘tomography,’ in order to try to recover depth information.

Another frontier of CMB research is the measurement of the absolute frequency spectrum of the CMB. It is remarkable that the COBE FIRAS experiment of 25 years ago still remains the best measurement of the absolute frequency spectrum, notwithstanding some improvement at low frequencies by the ARCADE balloon borne experiment. By contrast, great progress has been made improving on the COBE DMR first detection of the primordial CMB anisotropy, and much of this improvement derives from ground and balloon based experiments and not just the two post-COBE CMB space missions WMAP and Planck. While differential measurements can be carried out through the atmosphere, absolute measurements require subtractions that are not feasible. Technology has greatly improved since FIRAS, and an experiment called PIXIE³³ has been proposed to very roughly speaking redo the FIRAS experiment with polarization and with a sensitivity approximately two orders of magnitude better. We also note parenthetically that PIXIE also proposes to search for B modes with the same instrument (using a substantially different technique). For an interesting summary of the new science made possible through measuring the absolute spectrum, see Ref. 29 and references therein.

6. Conclusion

We have seen that observations of the CMB both of its anisotropies in temperature and polarization and of its absolute frequency spectrum have played a key role in putting modern cosmology on a firm observational footing, so that what is now known as the “standard model of cosmology” or the early universe is not just theoretical speculation. We should be careful not to exaggerate the successes of this model, because there remain a lot of open questions, and in certain respects (e.g., the functional form of the primordial power spectrum), the model provides what may be fairly described more as a fitting formula than a complete theory. For example, the standard model as proposed by Weinberg and Salam, even though theorists may not like it so much for various well justified reasons, has a well defined number of parameters — there are no free functional forms. Even if we admit massive neutrinos, which are now known to exist and often described as ‘physics beyond the standard model,’ one must admit that the few extra terms and parameters, which from the theoretical point of view hardly constitute a revolutionary update of the theoretical physics of the late 1960s and 1970s. Indeed there is room for a

compelling theoretical model realizing inflation that would provide a prediction for the functional form of the inflationary potential, or for an alternative to inflation. But this is a subject on which we have seen many papers, but unfortunately there have been no qualitative breakthroughs.

To my mind, the most interesting future challenge of CMB research is the search for primordial B modes. As explained above, the scalar power spectrum has already been characterized close to the ultimate limit imposed by cosmic variance. On the other hand, regarding B modes, all that we have for the moment is ever improving upper bounds. The last five years have seen a remarkable improvement in the quality of these bounds, to the point now that the best bounds on r derive from B modes and no longer from the shape of the TT power spectrum at $\ell \lesssim 100$. The bounds derived from the shape of the temperature spectrum are highly model dependent, whereas the bounds from B modes are extremely robust.

There remains substantial scope for improving on measurements of the B modes. The most ambitious projects currently in the planning stage aim to be able to make a detection of $r = 0.001$ at high statistical significance, and if one is very (perhaps unrealistically) optimistic about the unknowns (e.g., complexity of foregrounds, ability to overcome systematic uncertainties), one might hope to be able to push beyond the goal.

At this point, apart from the experiments already underway, several initiatives ambitious initiatives are being planned. In the suborbital class, there is the ground-based American S4 (“Stage 4”) program, whose details remain to be defined, aims to deploy of order (few) $\times 10^5$ detectors from the ground in order to detect primordial B modes and also map the lensing potential from the ground. What can actually be achieved from the ground is subject to considerable uncertainty on account of atmospheric interference and the paucity of bands for which the atmospheric contamination is not overwhelming.

From space three satellite missions are presently under consideration: the Japanese-led LiteBird mission (described in more detail in the contribution by Hirokazu Ishino in these proceedings), an ESA M5 proposal whose details are not yet defined, and PIXIE. The ESA M5 proposal could be similar to the previous COrE and COrE+ proposals, or it could take the form of a joint ESA-JAXA-NASA mission building on the success of the LiteBird JAXA/NASA joint phase A study now underway. Another possibility is a new version of the PIXIE proposal. In any case, it is clear that there still remains much exciting new science to be done in the area of CMB observation and it is difficult to predict exactly what path this field will take.

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References

1. M. Bucher, "Physics of the cosmic microwave background anisotropy," Int. J. Mod. Phys. D24 (2015) 1530004 (arXiv:1501.04288)
2. P.B. Gove, Ed., *Webster's Third New International Dictionary (unabridged)*, (Springfield, MA: Merrian-Webster, 1961)
3. E. Lerner, *The Big Bang Never Happened: A Startling Refutation of the Dominant Theory of the Origin of the Universe*, (New York: Times Books, 1991).
4. N.D. Birrell and P.C.W. Davies, *Quantum fields in curved space*, (Cambridge: Cambridge University Press, 1984)
5. R.A. Alpher, H. Bethe, and G. Gamow, "The origin of chemical elements," Phys. Rev. 73 (1948) 803
6. Planck Collaboration (P.A.R. Ade et al.), "Planck 2015 results. XIII. Cosmological parameters (arXiv:1502.01589)
7. Planck Collaboration (R. Adam et al.), "Planck 2015 results. I. Overview of products and scientific results," (arXiv:1502.01582)
8. A.P.S. Yadav and B.D. Wandelt, "Detection of primordial non-Gaussianity (fNL) in the WMAP 3-year data at above 99.5% confidence," Phys. Rev. Lett. 100 (2008) 181301 (arXiv:0712.1148)
9. Planck Collaboration (P.A.R. Ade et al.), "Planck 2013 results. XXIV. Constraints on primordial non-Gaussianity," Astron. Astrophys. 571 (2014) A24 (arXiv:1303.5084)
10. Planck Collaborations (P.A.R. Ade et al.), "Planck 2013 results. XVII. Gravitational lensing by large-scale structure," Astron. Astrophys. 571 (2014) A17 (arXiv:1303.5077)
11. D.N. Spergel, L. Verde, H.V. Peiris et al., "First Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Determination of Cosmological Parameters," Ap. J. Suppl. 148 (2003) 175 (arXiv:astro-ph/0302209)
12. D.N. Spergel et al., "Three-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Implications for Cosmology," Ap. J. Suppl. 170 (2007) 377 (arXiv:astro-ph/0603449)
13. R. Flauger, J.C. Hill and D.N. Spergel, "Toward an Understanding of Foreground Emission in the BICEP2 Region," JCAP 1408 (2014) 039 (arXiv:1405.7351)
14. The BICEP2 Collaboration (P.A.R. Ade et al.), "BICEP2 2014 I: Detection of B-mode Polarization at Degree Angular Scales by BICEP2," Phys. Rev. Lett. 112 (2014) 241101 (arXiv:1403.3985)
15. Planck Collaboration (R. Adam et al.), "Planck intermediate results. XXX. The angular power spectrum of polarized dust emission at intermediate and high Galactic latitudes," Astron. Astrophys. 586 (2016) A133 (arXiv:1409.5738)
16. The BICEP2/Keck and Planck Collaborations, "A Joint Analysis of BICEP2/Keck Array and Planck Data," Phys. Rev. Lett. 114 (2015) 101301 (arXiv:1502.00612)
17. Keck Array, BICEP2 Collaborations (P.A.R. Ade et al.), "BICEP2/Keck Array VI: Improved Constraints On Cosmology and Foregrounds When Adding 95 GHz Data From Keck Array," Phys. Rev. Lett. 116 (2016) 031302 (arXiv:1510.09217)
18. S. Das, T. Louis, M.R. Nolte et al., "The Atacama Cosmology Telescope: Temperature and Gravitational Lensing Power Spectrum Measurements from Three Seasons of Data," JCAP 04 (2014) 014 (arXiv:1301.1037)
19. R. Keisler et al., "A Measurement of the Damping Tail of the Cosmic Microwave Background Power Spectrum with the South Pole Telescope," Ap. J. 743 (2011) 28 (arXiv:1105.3182)
20. Planck Collaboration, "Planck: The Scientific Programme (also known as the Blue Book)," (2005) <http://sci.esa.int/planck/47334-planck-the-scientific-programme/>

21. C. B. Netterfield et al., “A Measurement by BOOMERANG of Multiple Peaks in the Angular Power Spectrum of the Cosmic Microwave Background,” *Ap. J.* 571 (2002) 604 (arXiv:astro-ph/0104460)
22. A.T. Lee et al., “A High Spatial Resolution Analysis of the MAXIMA-1 Cosmic Microwave Background Anisotropy Data,” *Ap. J. Lett.* 561 (2001) 1 (arXiv:astro-ph/0104459)
23. J. Kovac et al., “Detection of Polarization in the Cosmic Microwave Background using DASI,” *Nature* 420 (2002) 772 (arXiv:astro-ph/0209478)
24. P.J.E. Peebles, L.A. Page and R.B. Partridge, *Finding the Big Bang*, (Cambridge: Cambridge University Press, 2009)
25. A. McKellar, “Evidence for the Molecular Origin of Some Hitherto Unidentified Interstellar Lines,” *PASP* 52, (1940) 187
26. A. Kogut, D.J. Fixsen et al., “The Primordial Inflation Explorer (PIXIE): a nulling polarimeter for cosmic microwave background observations,” *JCAP* 2011 (2011) 025 (arXiv:1105.2044)
27. D.J. Fixsen et al., “The Cosmic Microwave Background Spectrum from the Full COBE FIRAS Data Set,” *Ap. J.* 473 (1996) 576
28. G.F. Smoot et al., “Structure in the COBE differential microwave radiometer first-year maps,” *Ap. J.* 396 (1992) L1
29. J. Silk and J. Chluba, “Next Steps for Cosmology,” *Science* 344 (2014) 586
30. T. Matsumura et al. “Mission design of LiteBIRD,” *J. Low Temp. Phys.* 176 (2014) 733 (arXiv:1311.2847)
31. K.N. Abazajian et al., “Inflation Physics from the Cosmic Microwave Background and Large Scale Structure,” *Astropart. Phys.* 63 (2015) 55 (arXiv:1309.5381)
32. K.N. Abazajian et al., “Neutrino Physics from the Cosmic Microwave Background and Large Scale Structure,” *Astropart. Phys.* 63 (2015) 66 (arXiv:1309.5383)
33. A. Kogut, D.J. Fixsen et al., “The Primordial Inflation Explorer (PIXIE): A Nulling Polarimeter for Cosmic Microwave Background Observations,” *JCAP* 07 (2011) 025 (arXiv:1105.2044)
34. M. Turner, “Cosmology Solved?,” (arXiv:astro-ph/9811447)
35. R. Weiss, “Measurements of the Cosmic Microwave Background Radiation,” *Ann. Rev. Astron. Astrophys.* 18 (1982) 489
36. A.C.S. Readhead and C.R. Lawrence, “Observations of the Isotropy of the Cosmic Microwave Background Radiation,” *Ann. Rev. Astron. Astrophys.* 30 (1992) 653