THE COSMIC MICROWAVE BACKGROUND

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Abstract

I review the discovery of the temperature fluctuations in the cosmic microwave background radiation. The underlying theory and the implications for cosmology are reviewed, and I describe the prospects for future progress.

1 Introduction

The discovery of cosmic microwave background temperature fluctuations in 1964 has revolutionised cosmology. Prior to 1992, one could only speculate about the initial conditions for structure formation. Primordial acausal curvature fluctuations were first detected by an experiment on the COBE satellite that mapped the sky on angular scales in excess of 5 degrees, much larger than the causal horizon of approximately one degree at last scattering. This provided the first glimpse of what was to come over the next ten years. Provided one adopted the inflationary prescription of scale-invariant fluctuations, one could make the connection to the long sought seeds of large-scale structure formation. But the connection was tenuous, and purely theoretical.

There were two stages to the discovery. As early as 1967, the prediction was made that intrinsic horizon-scale density fluctuations could be as large as 10 percent without exceeding the current limits on the cosmic microwave background isotropy at that time. These fluctuations were considered to be on scales in excess of the last scattering horizon and were imprinted acausally at the beginning of the universe. The connection with galaxy formation arising from primordial irregularities of infinitesimal amplitude, the current paradigm for
structure formation, was also made in 1967 [2]. The relic temperature fluctuations are causally generated from sound waves in the primordial baryon-photon plasma on the last scattering surface of the cosmic microwave background at redshift $z \approx 1000$.

The search for cosmic microwave background temperature fluctuations was long. Results from the COBE far infrared spectrophotometer (FIRAS) showed in 1990 that the spectrum of the cosmic microwave background did not deviate from a blackbody by more than 0.01% of its peak brightness. Large-angular scale fluctuations in the CMB were eventually discovered in 1992 using the COBE differential microwave radiometer (DMR) [3] at a level $\delta T/T \sim 10^{-5}$, to within a factor of two of the expectation from the twin hypotheses of structure formation by gravitational instability and a scale-invariant spectrum of primordial adiabatic density fluctuations. However, the extrapolation from the COBE observations to scales of direct interest to structure formation, from $\ell \sim 20$ to $\ell \sim 200$, where the spherical harmonic wave-number $\ell \approx 180^\circ/\theta$ for angular scale $\theta$, was large. It took nearly a decade after the COBE launch before direct detection of the elusive fluctuations that gave rise to large-scale structure was achieved.

Sub-degree scale temperature fluctuations from the surface of last scattering were finally confirmed, and in particular the first peak was measured, by a series of balloon and mountain-top experiments [4], [5], [6], [7], [8], [9], [10], that spanned the range $\ell \sim 20$ to $\ell \sim 2000$. The causal adiabatic fluctuations were amplified from primordial curvature fluctuations by subhorizon growth in the matter-dominated era. This enhancement was detected as a series of so-called acoustic peaks, the first and best-measured feature (known to better than ten standard deviations by the end of 2002) corresponding to the angular scale of the horizon at last scattering. The peaks are driven by sound waves in the primordial baryon-photon plasma, and the sound wave amplitude measures the seeds of present-day structure formation.

The theory of gravitational instability in the expanding universe as the driver of growth of structure from infinitesimal primordial density fluctuations, pioneered in a remarkable paper dating from 1946 [11], was dramatically confirmed. Gravitational instability accounts
for the origin of large-scale structure and in particular for the formation of the galaxies. The primordial structure was inhomogeneous at a level of around one part in 100,000. On comoving scales in excess of 100 Mpc, the universe is still uniform today and approaches this level on the horizon scale. However subhorizon growth means that the comoving scales of galaxy clusters (approximately 10 Mpc) were first nonlinear at a redshift of order unity, massive galaxies at a redshift of around 3, and dwarf galaxies at a redshift of order 10. These inferences come from measurement of the power spectrum of temperature fluctuations, from which the density fluctuation spectrum can be recovered. The discovery of the fossil fluctuations that seeded structure formation is a stunning intellectual achievement of the 20th century.

Complementary information comes from deep galaxy redshift surveys and from the line-of-sight correlations of intergalactic clouds viewed via Lyman alpha absorption against high redshift quasars. It is remarkable that the fluctuation spectrum measured at a redshift of 1000 agrees in shape and normalization with independent measurements of large-scale structure [12], [13]. These are performed at redshifts of 0.3 and 3, corresponding to the typical depths of the 2DF/SDSS galaxy samples and the Lyman alpha forest [14]. Even the bias factor, which measures the ratio of the variance in galaxy counts to dark matter density fluctuations, can now be inferred via a combination of any two of several independent techniques: large-scale clustering [15], CMB data [16], weak lensing [17], [18], and the galaxy cluster abundance [19]. A bias of approximately 4/3 is inferred on galaxy cluster scales. This means that the rms fluctuations in dark matter density are 75 percent of the variance in luminous galaxy counts sampled over randomly placed spheres of 10 Mpc diameter. Galaxy formation is only weakly biased.

2 Some history

The cosmic microwave background and the temperature fluctuations therein are two of the major predictions of the Big Bang the-
ory. Others are the expansion of the universe and the light element abundances. The latter motivated the cosmic microwave background prediction. Friedmann and independently Lemaître are credited with the first predictions of the expansion of space. Indeed Lemaître predicted a linear relation between galaxy redshift and distance, verified by Hubble in 1929. Curiously, Hubble never accepted the Big Bang interpretation of his redshift law as the expansion of space. It has even been speculated that Hubble’s reluctance to accept that the eponymous law was a fundamental contribution to the confirmation of the theory of the expanding universe may explain why Nobel recognition eluded him.

Gamow pioneered the predictions of element nucleosynthesis in the first few minutes of the Big Bang [20], but the important recognition by Hayashi in 1950 that the neutron abundance was determined by thermal equilibrium in the primordial plasma set the scene for the later precise predictions of the light element abundances. Gamow’s associates Alpher and Herman [21] realized in 1949 that the inference the universe necessarily was hot at the epoch of primordial nucleosynthesis implied that, in order to get a reasonable helium abundance, the present epoch radiation background was characterised by a temperature of 5 K. However they failed in any published work over the following decade to make the connection with an observable microwave background. Indeed, later papers speculated about a radiation temperature today as high as 50K.

The connection with observations was first attempted in discussions in 1962 by Zeldovich [22] and in 1964 by Doroshkevich and Novikov [23], who even interpreted a Bell Labs measurement of the atmospheric temperature as setting a limit of only 1 K on the cosmic radiation background to be evidence for an initially cold universe. But in effect an extraterrestrial signal was lurking in the measured antenna temperature. Evidence of absence did not guarantee absence of evidence, and the cosmic microwave background was discovered within a year via the epochal detection by Penzias and Wilson of what they described as an excess antenna temperature, isotropic in the sky. Penzias and Wilson did not initially realize the significance of their discovery, and the connection with the Big Bang was made in
a pioneering companion paper by Dicke and collaborators at Princeton, who had been searching, simultaneously and independently, for the cosmic microwave background. The Princeton group realized that the early universe would have been an ideal furnace for generating blackbody radiation. Dicke in particular, an experimentalist who was apparently unaware of Gamow’s work and was convinced that the Big Bang was cyclic, had long realized that light element synthesis in the Big Bang implied a present day blackbody radiation field at a few K, peaking at microwave frequencies.

Observations of the blackbody-like spectral dependence of the CMB accumulated over the next two and a half decades, but it was not until the launch of the COBE FIRAS interferometer that a definitive spectral measurement was forthcoming. FIRAS confirmed the CMB spectrum was that of a blackbody at $2.725 \pm 0.002$K, with a precision limited only by that of the on-board calibration source [24]. The cosmic blackbody spectrum is comparable to that of the best laboratory blackbody spectral determination.

Parallel theoretical developments focussed on angular variations in the CMB temperature. In 1967, Sachs and Wolfe had predicted that primordial curvature fluctuations could exist on horizon scales, $\sim 1000$ Mpc, generating temperature fluctuations on large angular scales with an amplitude of order 1 percent. These would have been acausal and attributable to the initial conditions of the Big Bang. Subsequent studies of the first instants of the universe led to the development in 1981 of inflationary cosmology, which predicted adiabatic, gaussian fluctuations that were boosted from quantum fluctuations to macroscopic scales during an early de Sitter phase. The universe expanded exponentially during a brief moment, triggered by the spontaneous breaking of the GUT symmetry at a temperature of about $10^{16}$ GeV. The theory also predicted that the fluctuations should be approximately scale-invariant, although the amplitude was not specified, in agreement with earlier conjectures that have become known as the Harrison–Zeldovich spectrum ([25], [26], [27]). Many versions of inflation also subsequently predicted this, but perhaps the most noteworthy prediction of inflation is that the universe should be flat ([28], [30], [29]).
Another pre-inflationary prediction, and one that inflation did not, and could not, provide, was that of the strength of the primordial density fluctuations. This yielded the first quantitative estimate of the fluctuations that are required to have seeded structure by gravitational instability-induced growth. A simple prediction based on adiabatic fluctuations required $\frac{\delta T}{T}$ to be a few parts in ten thousand at last scattering on angular scales of a few arc minutes in order to have formed galaxies and clusters by the present epoch [2]. The prediction simply utilized the adiabatic relation that, if recombination were instantaneous, would give $\frac{\delta T}{T} \sim \frac{1}{3} \frac{\delta \rho}{\rho}$.

The current prediction is about a factor of 10 smaller than implied by this simple expression. What causes the diminution? The realization that decoupling of the two fluids was not instantaneous [31] results in a substantial decrease of the relic temperature fluctuations [32]. Modern treatments, which incorporated cold dark matter, were first performed in 1984 ([32], [33]), and allow fluctuation growth after the epoch of matter-radiation equality but prior to last scattering, anticipating a peak value $\frac{\delta T}{T} \sim 3 \times 10^{-5}$ on an angular scale of about half a degree. This corresponds to the horizon scale at last scattering.

The predictions refer to causal fluctuations generated by gravitational instability on subhorizon scales during the era of matter domination, and apply on the largest scales where structure is seen, namely galaxy clusters and superclusters, and hence to angular scales of order tens of arc minutes. The coherent peaks in the radiation density are due to compressions and rarefactions of sound waves in the primordial plasma as viewed at last scattering. The occurrence of multiple peaks in the radiation power spectrum was first described in 1976 [34], and were only accurately described as a generic description developed from a multipole expansion of the CMB sky in 1981 [35]. This approach incorporated the first application to temperature fluctuation predictions of the coupling of the primordial photon-baryon plasma by the Boltzmann equation, originally given in a classic paper in 1970 [26]. The latter paper indeed reported the existence of coherent baryon oscillations of the adiabatic mode in the matter-radiation plasma at matter-radiation decoupling, also independently noted by [56]. These two papers quantify the so-called Sakharov oscillations [37] in the mat-
ter power spectrum. These matter power spectrum oscillations have recently been detected, albeit with modest significance, in the 2DF galaxy survey [38].

Progressively more detailed discussions in the 1990s describe a series of acoustic peaks, interpreted in the context of inflationary amplification of quantum fluctuations. These result in temporally coherent fluctuations on the surface of last scattering at $z \sim 1000$ that are driven by the growing adiabatic mode of linear theory.

The connection between $\delta T/T$ and structure formation presented a definitive experimental target in the 1970s and 1980s, although the goalposts were moved in 1984 when cold dark matter was first included into the computational recipe. The prevalence of weakly interacting dark matter that dominates the baryon density by a factor $\sim 10$ means that substantial fluctuation growth occurs between the epoch of the onset of matter domination at $z \sim 4 \times 10^3$, prior to last scattering at $z \sim 10^3$. This reduces the predicted fluctuation strength by a factor $\sim 4$, and significantly modifies the detailed structure of the radiation power spectrum.

Upper limits were successively improved. Only with the COBE DMR detection in 1992 of large angular scale fluctuations attributed to the acausal conditions at the beginning of the universe was it realized that the elusive, causally amplified, subhorizon, fluctuations on the last scattering surface that seeded the observed large-scale structure might be within reach once foregrounds could properly be accounted for.

A series of experiments led to multifrequency measurements that could eliminate dust and synchrotron galactic foregrounds. These had plagued much of the earlier work, but bolometer sensitivities improved and microwave receiver noise temperatures were reduced while bandwidths were increased. The backgrounds could be modeled with sufficiently high sensitivity, wide spectral frequency and sky coverage. The definitive measurements came in at the beginning of the new millennium, from the BOOMERANG and MAXIMA bolometric balloon experiments and the DASI, VSA and CBI mountain-based interferometers.

The conclusions have revolutionized cosmology. The hypothesis
of structure formation by gravitational instability of primordial infinitesimal inhomogeneities has been verified. The flatness of the universe is measured: the first peak occurs at \( \ell = 215 \pm 10 \) and requires \( \Omega_0 = 1.02 \pm 0.06 \). The power spectrum of the fluctuations is described by a constant index power law fit by \( n = 0.96 \pm 0.06 \), essentially the scale-invariant expectation. The baryon abundance is confirmed to be \( \Omega_b h^2 = 0.021 \pm 0.04 \). All of these quantities are cited at 68\% confidence (e.g. [10], [39]).

\section{Some theory}

Detection of the CMB fluctuations is a triumph of the simplest Big Bang cosmology: confirmation of a linearly perturbed expanding universe. To describe the anisotropies in a Euclidean geometry, one expands the temperature field on the celestial sphere in spherical harmonics

\[
\frac{\Delta T}{T}(\hat{n}) = \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\hat{n}). \tag{1}
\]

By definition the mean value of the \( a_{\ell m} \) is zero.

The correlation function (or 2-point function) of the temperature field \( C(\theta) \) is the average of \( \Delta T/T(\hat{n}_1)\Delta T/T(\hat{n}_2) \) across all pairs of points in the sky \( (\hat{n}_1, \hat{n}_2) \) separated by an angle \( \theta \) (\( \cos \theta = \hat{n}_1 \cdot \hat{n}_2 \)). One usually assumes statistical isotropy and Gaussian statistics. One can now write down [40] a multipole expansion

\[
C(\theta) = \frac{1}{4\pi} \sum_{\ell} (2\ell + 1) C_\ell P_\ell(\cos \theta) \tag{2}
\]

where \( P_\ell(\cos \theta) \) are the Legendre polynomials and the \( C_\ell \) are the multipole moments,

\[
C_\ell = \sum_{m=-\ell}^{\ell} a_{\ell m}^* a_{\ell m}, \tag{3}
\]

and where \( \ell \propto \theta^{-1} \).
Each $C_\ell$ comes from averaging over $2\ell + 1$ modes, and the sample variance error on $C_\ell$ is

$$\frac{\delta C_\ell}{C_\ell} = \sqrt{\frac{2}{2\ell + 1} f_{\text{sky}}^{-1/2}},$$

(4)

where a fraction $f_{\text{sky}}$ of the sky is observed [41], [42]. The contribution to the logarithmic power is usually written as $\ell(\ell + 1)C_\ell$, this combination being constant at low $\ell$ for scale-invariant fluctuations.

The radiation power spectrum shows two characteristic angular scales. A prominent peak occurs at $\ell \approx 220$ or about 30 arc-minutes. This is the angular scale that corresponds to the horizon at the moment of last scattering of the radiation. The corresponding comoving scale, corresponding to the wavelength of a wave that just spans this horizon, is approximately 100 Mpc. The second scale is the damping scale of about 6 arc-minutes, where the finite thickness of the last scattering surface just spans a wave of comoving scale around 10 Mpc and damps out temperature fluctuations on smaller scales [43].

The principal features that separate these scales are the Sachs-Wolfe plateau at low $\ell$, the series of peaks between $\ell = 200 - 2000$, and the damping tail. The peaks are the relic of coupled photon-baryon oscillations, in effect sound waves in the primordial plasma, at the epoch of last scattering of radiation and matter. One finds a series of peaks because the growing mode of fluctuations is the only surviving mode, and are phase-locked on super-horizon scales most likely due to their inflationary origin. Waves that just crest at last scattering produce the first adiabatic peak in the CMB. Waves of half the last horizon scale also crest, as do smaller waves until damping sets in at about 10 percent of the wavelength of the first acoustic peak. The peaks in the power spectrum are associated with successive maxima and minima of density waves in the coupled photon-baryon plasma, alternately in and out of phase with the dark matter potential wells that dominate the gravity and correspond to compressions and rarefactions on the last scattering surface that in turn generate hot spots and cold spots in the radiation on the last scattering surface. In quadrature, these are represented as a series of peaks in the power spectrum.

Coherent peaks are generated because an inflationary, or more
generally, a very early, origin means that only the growing mode of fluctuations are present, and since no growth occurs on superhorizon scales, the phases of the waves can only evolve once growth commences after entering the horizon. Hence for example any wave that just spans the horizon at last scattering has the same phase. Any wave that spans half the horizon at last scattering has had exactly the same amount of subhorizon growth, so these too are in phase. Now the wave amplitude is proportional to $\cos(kt/a)$, where $k/a$ is the wave-number, $a(t)$ is the cosmological scale factor, and the initial conditions are such that the amplitude must be constant (and independent of wave-number for a scale-invariant spectrum) on super-horizon scales $2\pi a/k \gg ct$. This is the Sachs-Wolfe effect. The wave cresting at last scattering $t_{LS}$ gives the first peak, and there is a series of compression/rarefaction peaks at $kt_{LS}/a = (n + 1)\pi$, $n = 0, 1, 2, \ldots$, and Doppler peaks at $kt_{LS}/a = (n + 1/2)\pi$, $n = 0, 1, 2, \ldots$. The compression mode is found to be dominant.

The Doppler effect [36] generates smaller peaks that are 90 degrees out of phase with the compression mode, and the effect of enhancing the baryon component is to strengthen the compressions relative to the rarefactions because of the baryonic contribution to the gravity [44]. The baryon density controls the rarefaction amplitude relative to the compression amplitude, so the odd-even alternation of peak strengths enables $\Omega_b h^2$ to be read off the sky.

The influence on the radiation power spectrum of spatial curvature with accurate matter-radiation coupling was first computed in 1981 [45]. In curved space, a generalised multipole expansion is necessary. One finds that spatial curvature modifies the angular distribution but its effects are readily disentangled. In the modern language of acoustic peaks, the peaks are found to be shifted by a factor of order $\Omega^{1/2}$ towards smaller angular scales in hyperbolic spaces, for progressively lower $\Omega$ [46], [47]). Confirmation of the flatness of the universe via measurement of the peak location represents a major triumph of inflationary cosmology.

There are many complications, some welcome, some less so. The overall amplitude of the peaks is largely controlled by $\Omega_m$, or more precisely the ratio of matter to radiation densities and by $\Omega_\Lambda$. There is
a degeneracy between $\Omega_m$ and $\Omega_\Lambda$ that cannot be resolved by the CMB alone [48]. Reionization suppresses the total power, and in particular all of the peak heights, and can be constrained [49]. In fact, $\Omega_\Lambda$ results in lensing of the peaks and redistributes power to small scales, so only very high $\ell$ measurements can help break this degeneracy [50]. In practice, the degeneracy is best broken by correlation with deep redshift surveys since the effects of $\Omega_\Lambda$ are most important at $z \lesssim 1$ [51].

4 Implications

One frontier has recently been breached in the CMB. The first detection of polarization has been reported by the DASI interferometer. The polarization in an FRW universe is due to the anisotropy of the Thompson scattering cross-section combined with the intrinsic quadrupole component of the radiation fluctuations [52]. This results in polarization that typically peaks at the angular scale of the last scattering surface. Detection provides additional confirmation of the standard model.

The cosmic microwave background fluctuations provide an important probe of inflation. This arises in two ways. Firstly fluctuations on angular scales larger than a degree are acausal at last scattering and so are generated at GUT scales during inflation or even earlier as part of Planck era physics. One is directly viewing the impact of quantum fluctuations. Secondly, gravity waves are generically generated as a tensor mode in inflationary models. These contribute only to the large angular scale anisotropies, since the tensor mode is incompressible and redshifts away on subhorizon scales once the universe is matter-dominated [53]. One can constrain the tensor/scalar ratio from the ratio of the low $\ell$ amplitude to the peak heights, combined with the 2DF power spectrum, to be less than about 70 percent [55].

Polarisation of the temperature fluctuations will eventually provide a much more constraining probe of both the ionization history and primordial gravity waves [54]. In general, the polarisation can be separated into two modes that can be expressed as the gradient and
the curl of a potential. Electron scattering of a radiation field with an intrinsic quadrupole component generates the gradient mode of polarisation. Gravitational lensing couples this gradient to the curl mode. However only gravity waves give an intrinsic curl component of polarisation. This provides a unique signature that can in principle be disentangled from the induced curl polarisation, and should be detectable on degree scales or larger at the 0.5µK level for typical inflationary models [56].

Reionisation further complicates matters, since late electron scattering also polarises the CMB. For typical models, the detailed $C_\ell$ spectrum of scalar-induced polarisation should be distinguishable at a level of 5–10µK on small angular scales and around 1µK on large scales ($\ell \lesssim 200$) [57]. Late reionization produces the gradient mode of polarisation and has a characteristic low $\ell$ bump corresponding to the horizon size at reionization [58], [59]. In fact the gradient terms contribute to polarisation at a level of about 0.1$\delta T/T$, and this has been detected by the DASI interferometer on 5-30 arc-minute scales [60]. The MAP satellite should be capable of seeing the characteristic peak associated with reionization, if this occurred at $z > \sim 10$.

The tensor contribution to the curl component of polarisation is only of order 0.01$\delta T/T$, and detection will require dedicated experiments that must await the post-Planck era, 2008 or later. Detection of the gravity wave mode would provide another powerful confirmation of inflation, which generically predicts a mixture of scalar and tensor relic fluctuation modes with approximately scale-invariant spectra.

In contrast, pre-Big Bang and ekpyrotic models usually predict blue spectra of primordial gravity waves that would not leave any detectable CMB relic polarisation. Intrinsic non-gaussianity is an aspect of generic very early universe models that could also help constrain inflation. There are hundreds of variants of inflationary cosmology, and it is difficult to come up with any definitive tests, other than perhaps the prediction of flatness of space. Multiple scalar fields that drive several phases of inflation, or interact during the primary phase, will lead to non-gaussian fluctuations. Topological defects such as cosmic strings or textures that are generated during post-inflationary reheating are a promising source of non-gaussian fluctuations on small angular scales,
although these must be subdominant with regard to structure formation.

At high \( \ell \), the observed damping provides an independent probe of \( \Omega_b \), and confirmation of the physics of last scattering. Beyond \( \ell \sim 2000 \), non-linear effects play an important role. The most prominent of these is the Sunyaev-Zeldovich (SZ) effect, which is the cumulative contribution of hot gas in distant unresolved clusters along the line of sight, and is uniquely distinguishable by its spectral characteristics as an apparent deficit below 218 GHz in the rest frame and excess at higher frequency, relative to the CMB. There is a reported 2\( \sigma \) detection at \( \ell \sim 2500 \) by the CBI experiment which however only covers a narrow frequency range near 30 GHz \cite{61}.

The Ostriker-Vishniac \cite{62} and Rees-Sciama \cite{63} effects are also of interest at \( \ell \gtrsim 3000 \), due respectively to correlations of linear compressions and rarefactions with Doppler contributions along the line of sight and to traversal by CMB photons across the time-dependent potential wells associated with forming galaxy clusters, respectively. These anisotropies are expected to amount to only a percent or so of the SZ effect, as also is the kinematic SZ effect. However the challenge of detecting secondary fluctuations is important, since they probe the epoch of reionisation. Another aspect that is characteristic of secondary fluctuations is that they are expected to be intrinsically non-Gaussian, as well as being anti-correlated with the primary fluctuations. In general, reionization damping of primary fluctuations generates secondary fluctuations and enhances the polarisation: a recent discussion is given in \cite{64}.

The acausality of large angular scale fluctuations (\( \gtrsim 1^\circ \)) means that they were generated either as initial conditions or by an early de Sitter phase of inflation. The latter occurred in the first \( 10^{-35} \) second, and amplified quantum fluctuations onto macroscopic scales. An example of a novel approach to initial conditions comes from the ekpyrotic cosmology. This model dispenses with inflation and sets up the fluctuations in a pre-Big Bang phase that can be identified with the past history of two colliding branes. The brane intersection signals the initial moment of the Big Bang at the Planck time. This is also a singularity in space-time, and the calculations of the emergent density
fluctuations are controversial.

The synthesis of baryons occurs at electroweak (100 GeV) or GUT \(10^{16}\) GeV) scales, and is responsible for the specific entropy of the universe, that is, the number of photons per baryon observed in the CMB. It is tied in with lepton synthesis and generation of lepton number \(L\), since \(B - L\) is generally conserved in subsequent phase transitions that may dilute any primordial baryon number \(B\). The blackbody spectrum itself was generated in the first hours of the Big Bang. Double Compton scattering and bremsstrahlung are the key processes responsible for thermalisation. An essentially perfect blackbody is generated. No trace of thermalization processes is left, other than by possible late energy injection after the thermalization epoch.

The matter and radiation remain coupled until a redshift of about 1000. Hence the temperature fluctuations trace the degree of matter inhomogeneity over the first 300,000 years of the universe. One mostly measures the imprint of density fluctuations on the last scattering surface. These dominate the acoustic peaks. There is also a contribution at lower \(\ell\) from the integrated Sachs-Wolfe effect, both before and after last scattering, due to the decay of the ratio of the radiation to the matter densities. The temperature fluctuation mapping has led to an era of precision cosmology. One measures in addition to \(\Omega_0\) and \(n\), \(\Omega_b\) as well as a combination of \(\Omega_\Lambda\) and \(H_0\). With independent determinations of \(\Omega_m\) from large-scale structure, the standard model is well defined and well constrained.

5 Towards the Future

There are some 10 parameters that describe the CMB fluctuations, in addition to the 6 or so that characterise the standard model of cosmology. What is remarkable is that precise measurements of the CMB fluctuations can potentially measure almost all of these parameters with unrivalled precision. There are degeneracies, most notably between \(\Omega_m\) and \(\Omega_\Lambda\), but these can largely be resolved by cross-correlating with other data such as wide area weak lensing surveys.
These are exciting times for the cosmic microwave background, especially in combination with other data sets. The precision of the measurements is vastly superior to that of a decade ago. The overall picture is one of consistency with what is rapidly emerging as the standard model of cosmology.

There are less conventional issues that the CMB may eventually tackle. Gravity could change on very large scales, and the CMB uniquely probes the largest scales via the integrated Sachs-Wolfe effect, thereby providing a potentially unique probe of exotic gravity models \[65\]. The topology of the universe is not predicted by general relativity, or for that matter by quantum gravity. The CMB may provide the only means of ever detecting a topological signature of space-time. A flat, compact topology can undergo inflation from a quantum origin \[67\]. If the topological scale is on the order of the horizon scale, a detectable imprint in the form of a non-Gaussian pattern is generated on the CMB sky \[67\]. The existing COBE data eliminate all toroidal topologies if the topological scale is of order the present horizon scale or less \[68\]. The universe is locally isotropic but globally anisotropic in many of the topological representations, which, in the case of a flat universe, only amount to a handful of more general possibilities. It will be interesting to eventually explore some of the resulting patterns with more sensitivity and better resolution \[69\].

One can hope to probe the beginning of the universe; indeed, one already does this with large angular scale fluctuations. There is considerable support for inflation from the observed flatness of the universe, as well as from the approximate scale invariance of the power spectrum and the coherence of the acoustic peaks, although one hesitates to cite these latter two predictions as robust inferences from a theory which is neither unique nor able to account for the amplitudes of the peaks. The acausality at the epoch of last scattering on large angular scales could equally be created in the quantum chaos of the Planck epoch or even earlier, via pre-Big Bang physics, all that is required being phase coherence on superhorizon scales of matter and radiation fluctuations. The polarization signal of a relic gravity wave background presents the ultimate challenge, and the ultimate probe.

Most of this is for the future. At present, one has some noteworthy
highlights. Gravitational instability theory of structure formation has been verified. The universe has been found to be spatially flat. The CMB radiation power spectrum has provoked the death of topological defects as a significant source of seeds for structure formation. A purely baryonic universe can be discarded. This is remarkable progress in modern cosmology.

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