On the observability of the early universe

Marco Bersanelli
Department of Physics, University of Milan, Italy

Abstract

In the framework of contemporary cosmology, the age-old aspiration to inquire the outer limits of the universe translates into our effort to observe the initial stages of cosmic history. Thanks to a fortunate combination of astronomical circumstances, and pushing mm-wave technology to its limits, today we are able to image the early universe in great detail, back at a time ($t \sim$ 380,000 yr) when cosmic age was only 0.0027% of its present value. The state of the art in the field has been set by the ESA Planck mission, launched in 2009, dedicated to precision measurements of the cosmic microwave background (CMB). Planck observed the full sky for 4 years in a wide frequency range, reaching μK sensitivity both in temperature and polarization. The latest results, published by the Planck Collaboration in 2018, are in exquisite agreement with the simplest 6-parameter ΛCDM model and constrain the main cosmological parameters with percent-level accuracy. Furthermore, the Planck data yield insight on the very early universe ($t \sim 10^{-35}$s), opening the way to a new generation of experiments searching for the possible signatures of primordial gravitational waves in the CMB polarization pattern.

Keywords

cosmology, Planck mission, cosmic microwave background, primordial gravitational waves, CMB polarization patterns.

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1. The cosmic edge in history

The challenge of exploring what lies far away from us is as old as humankind. In every epoch, different cultures speculated about the shape and nature of the most distant regions of the cosmos. In ancient Greece, the Aristotelian school envisioned a geocentric universe enclosed within a well-defined spatial boundary, the *Primum Mobile*, the ultimate source of all motions. The most successful version of such worldview was the Ptolemaic model, a highly sophisticated geometrical structure combining a multitude of circular uniform motions capable of accounting for all celestial movements observable at the time. In the middle ages, when the ancient Greek authors were rediscovered, the Aristotelian-Ptolemaic model was enthusiastically adopted and reinterpreted within their new culture. The edge of the physical universe was still the *Primum Mobile*, but now it was surrounded by a further sky, the *Empyrean*, inhabited by the angelic beings and by God himself. In a profound poetic and geometrical intuition, Dante Alighieri suggested that the outer rim of the *Empyrean* coincides with a point of light, as if placed at the antipodes of the Earth in a non-Euclidean, 3-D spherical space[1].

The onset of the heliocentric paradigm in the 16th century opened a new era in the notion of what lies at great distance from us. In fact, the most revolutionary aspect of the Copernican paradigm probably concerned the periphery of the universe, rather than its centre. The daily movements of the stars were now explained in terms of Earth's motions, thus dismissing the need of that huge crystal sphere to hold the stars. Furthermore, the lack of detection of parallax effects

[1] A reading of the geometry of Dante's universe in terms of non-Euclidean geometry was first suggested by Speiser (1925) and developed by other authors (e.g. Peterson, 1979; Bersanelli, 2018).

required stars to be placed at very great distances, now floating in boundless space. The introduction of Newtonian physics did the rest to consolidate the concept of an infinite, Euclidean, absolute space.

With the advent of relativistic cosmology, the concept of "distant universe" entered yet another era. The realization that we live in an expanding space implies that the average properties of the universe (e.g., average density, temperature, etc.) change with time. Furthermore, by observing sources at increasing distances we see them at progressively remote epochs in the past. Because the expansion started at a finite time in the past, some 14 billion years ago, there is an ultimate horizon defining the extension of space we can observe, i.e., what lies within the distance light could travel since the beginning of the universe[2]. In our uniform and isotropic universe (on large scales) any direction in the sky displays to our observation essentially the same past cosmic history. But how far back can we actually see? Today we routinely observe galaxies that are some 12-13 billion light years away, and therefore belong to a relatively young universe. Can we receive light from anything further away? Or, which is the same, can we look further back towards the beginning of the universe?

In 1965, Arno Penzias and Robert Wilson serendipitously discovered[3] that the dark background of the sky is not completely lightless, but it glows with a diffuse, weak, uniform luminosity. This fossil light, named cosmic microwave background (CMB), is the remnant of the initial hot state of the universe. The CMB photons were released when expansion cooled the temperature below 3000 K and the first neutral atoms formed. This took place when the universe was 380,000 years old, or only 0.0027% of its present age, well before

[2] For an excellent conceptual discussion of cosmic horizons see (Harrison, 1981).

[3] The key original discovery papers are (Penzias and Wilson, 1965; Dicke et al., 1965). For a complete historical account see (Peebles, Page Jr and Partridge, 2009).

the formation of stars and galaxies. As matter became neutral, the universe quickly became transparent to light. At that time the wavelength of the cosmic photons was $\lambda \sim 1\mu$m, i.e., in the near-infrared. Since then, cosmic expansion red-shifted the photons by a factor $z \sim 1100$, moving them into the microwave range ($\lambda \sim 1$mm).

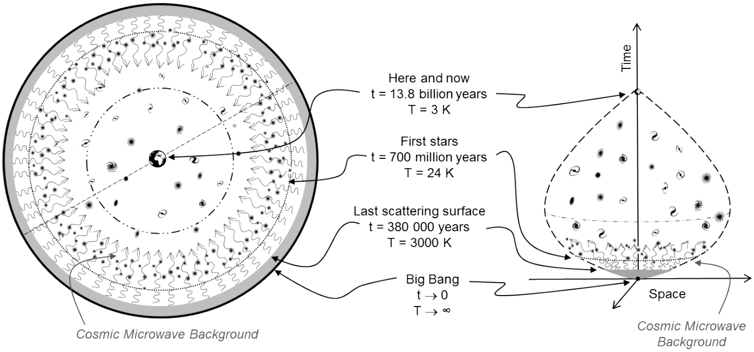

Figure 1: Space-time schematic of our observable universe, showing some of the key phases of cosmic evolution: the Big Bang, the last scattering surface releasing the CMB photons, the formation of the first stars, our present time and location. Left: events are shown in spherical symmetry as they appear to our observation; right: the same events are depicted on our past light cone.

The region where the CMB photons last interacted with matter is called "last scattering surface": it is a sort of cosmic photosphere encompassing the whole observable universe (Figure 1). Note however that when those photons were emitted, the size of the last scattering surface was 1100 times smaller than it is today, only $\sim$0.1% of the present scale. That relatively small surface is what we actually "see" when we observe the CMB. Therefore, even though the dark background of the sky surrounds us in all directions, and appears to us as the largest cosmic sphere, it is much smaller than the space occupied by galaxies and stars it contains. In remarkable analogy with Dante's cosmos, looking up in any direction of the sky we literally look towards a single point, the origin of the universe.

2. Observability

The CMB was not released by any particular source, rather, by the universe itself. Every cubic centimeter of space contains about 500 CMB photons with the energy distribution of a pure blackbody[4] at a temperature $T_0 = 2.725 \pm 0.001$ K. While extremely cold, the energy density of the relic radiation far exceeds that of light produced by all sources in the universe: about 95% of the total photon energy today is contained in the CMB, while all stars, galaxies, quasars, gamma ray bursts, and any other object account for the remaining 5%.

While the CMB photons fill the universe, it is far from obvious that we have the possibility to detect them. This is possible - and, in fact, we can measure them in great detail - only thanks to a number of favorable conditions both in our global and local astronomical environment.

First, one needs a highly transparent universe. And indeed, despite the enormous number of galaxies and clusters distributed in cosmic space, the voids between them are huge and our universe is essentially empty. This is a byproduct of the high efficiency of the galaxy formation process. The cosmic photons in their 14-billion-year journey traveled nearly unperturbed in the ultra-low opacity cosmic medium. Except in the direction of clusters of galaxies (whose hot plasma interacts with the CMB producing the Sunyaev-Zel'dovic

[4] High precision measurements of the CMB spectrum were established by the COBE/-FIRAS experiment (Mather et al., 1994; Fixsen, 2009).

effect) and of extragalactic radio and IR sources, the CMB photons bring to us a very faithful image of the universe at the time of decoupling, redshifted by a factor of $\sim 10^3$.

Second, our galactic environment should not contaminate too much the CMB radiation. When entering our galaxy, the CMB photons get mixed with microwave and mm-wave photons produced within the Milky Way. These come mainly from synchrotron radiation by electrons spiraling in the Galactic magnetic field; from free-free radiation produced in the ionized medium (HII regions); and from thermal and rotational emission by cold interstellar dust. Synchrotron and dust emission also produce linearly polarized components.

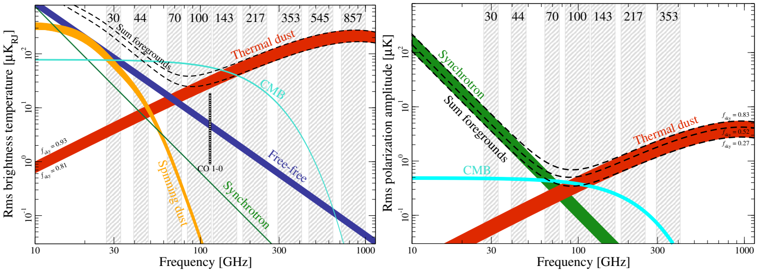

Figure 2: Observed rms brightness temperature of Galactic diffuse emissions and of the CMB as a function of frequency for intensity (left) and for polarization (right). For temperature, each component is smoothed to an angular resolution of 1 degree, and the lower and upper edges of each line are defined by masks covering 81 and 93% of the sky, respectively. For polarization, the corresponding smoothing scale is 40 arcmin, and the sky fractions are 73% and 93%. In the spectral region around ∼70GHz the CMB is higher or comparable to foreground emissions. The vertical shades represent the frequency bands observed by the Planck satellite (Planck Collaboration I, 2018) [Credits: ESA and the Planck Collaboration].

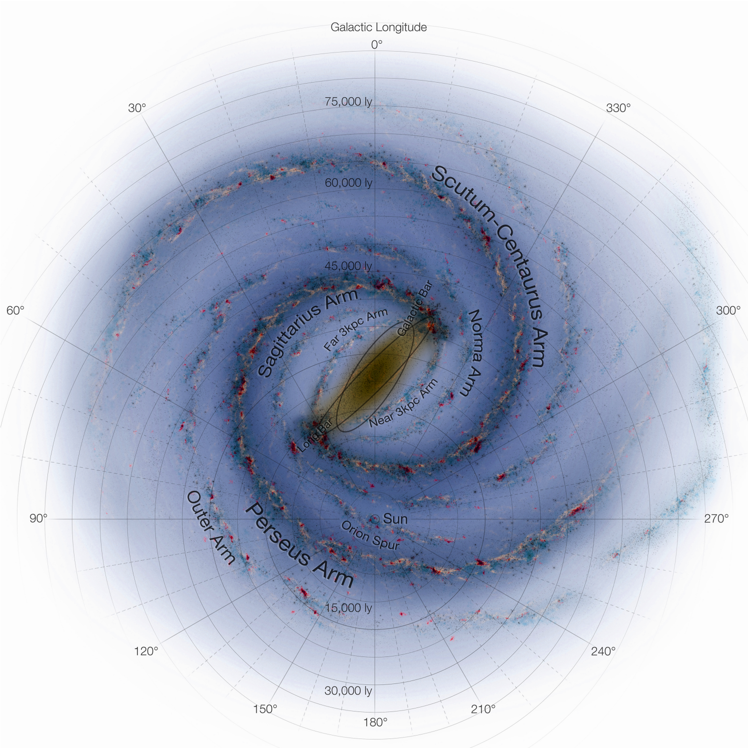

Figure 3: A reconstruction of the shape of the Milky Way, a barred spiral galaxy. The Solar System is located in a relatively low density region between the prominent Perseus arm and the Scutum-Centaurus arm [Credits: NASA/JPL-Caltech/R. Hurt, SSC/Caltech].

Due to a happy coincidence of nature, the maximum of the CMB blackbody spectrum lies close to a minimum of the combined diffuse emission from the interstellar medium of our galaxy and from extragalactic sources. As a result, the combined foreground signal in total intensity (temperature) and polarization, in the 1-10 mm range and away from the galactic plane, is lower or comparable to that of the CMB (Figure 2).

Of course, the situation is highly dependent on our vantage point within the Milky Way. Our Solar System is located between two prominent spiral arms, in a relatively low density region (Figure 3). Seen from here, the local diffuse radiation, while adding non-negligible level of contamination, is just weak enough to give us a chance to measure the CMB. Were our planet placed too deep into the galactic center, or inside a major spiral arm, we would be deprived of the possibility to image or even detect the CMB.

3. Cosmic seeds

Since the early 1990s we know that the intensity of the CMB in different direction of the sky is not completely uniform. This was expected because, in order to explain the formation of galaxies under the action of gravity, density perturbations needed to be present already at the time of last scattering. Since the CMB photons are influenced by the gravitational potential at decoupling, their angular distribution traces such early density perturbations and must exhibit a low level of anisotropy. In 1992, NASA's COBE satellite first detected CMB anisotropies with amplitude 0.001% at angular scales larger than 7 degrees (Smoot et al., 1992). The COBE pioneering discovery motivated several experiments from ground and stratospheric balloons in the following decade. In 2000, NASA launched the WMAP satellite which obtained full-sky maps of the CMB fluctuations with sub-degree resolution and much improved sensitivity (Bennett et al., 2003; Hinshaw et al., 2007). The Planck satellite, launched in 2009 by ESA, was designed as a third generation CMB satellite to obtain a definitive measurement of CMB anisotropies at all relevant angular scales.

The reason for such great experimental effort is that CMB anisotropies contain a gold mine of cosmological information. The CMB structure at sub-degree scales traces density and velocity patterns at the last scattering surface produced by acoustic oscillations in the primordial plasma. The details of the statistics of the CMB across the sky, therefore, depends sensitively on the physical conditions of the plasma, which in turn depend on key parameters such as the total energy density, Ω_{tot}, the abundance of baryonic and dark matter, Ω_b and Ω_c, the expansion rate (the Hubble constant $H_0 = 100h$ km s^{-1}Mpc^{-1}), the curvature of space, Ω_k. The observed CMB pattern is also sensitive to the spectrum of initial fluctuations that initiated the acoustic oscillations in the very early universe. These are parametrized by an amplitude A_S and a spectral index and n_S. In conclusion, an accurate measurement of CMB anisotropy over all relevant scales (full-sky to few arcmin) can in principle lead to precise measurements of many crucial cosmological parameters.

Further unique information to constrain the cosmological model is contained in the CMB polarization. A polarized component correlated with the temperature anisotropies, with $\sim$10% of their amplitude, is expected as a consequence of local quadrupole anisotropy at the last scattering surface. This polarization signal, called "E-mode", has been detected by a number of experiments[5] at the expected level (few μK). These data yield constraints on cosmological parameters complementary to those gained from temperature anisotropy, and help remove degeneracy.

[5] The first detection of CMB polarization was achieved in 2002 by the DESI experiment, operated at the South Pole (Leitch et al., 2002).

Another yet unobserved component of the CMB polarization, if detected, would provide a direct clue of the very early universe. According to the inflation scenario, first proposed by Linde and Kirshnitz in 1976 and independently by Guth in 1980, an initial ($t \sim 10^{-35}$s) superluminal expansion of space generated a stochastic field of gravitational waves (see Guth, 1997). Such perturbations must have produced a specific polarized pattern in the CMB photons, called “B-modes”. This is independent and observationally distinguishable from the “E-modes”. Inflation does not predict a specific amplitude of the B-modes, but it does indicate that the amplitude of the primeval gravitational waves (and therefore the CMB polarization) is proportional to the square of the energy scale at which they were generated. Therefore, if detected, the B-modes polarization would provide strong evidence of inflation and, in addition, would determine the energy scale at which it occurred.

How many parameters are needed to describe the global properties of the universe? The so-called standard ΛCDM cosmological model, within the framework of general relativity, assumes major contribution from a cosmological constant, Λ, accounting for the observed cosmic acceleration, and from cold dark matter (CDM). Its simplest version also assumes a flat geometry and fixes to standard values all parameters except for six of them, which can be treated as six degrees of freedom to be determined by observations.

To compare data to theoretical models, it is convenient to express the CMB fluctuations in intensity and polarization in terms of power spectra. The CMB pattern on the sphere, $\Delta T(\theta, \varphi)$, calibrated in brightness temperature, can be expressed as a linear combination of the spherical harmonics $Y_{l,m}(\theta, \varphi)$:

$$\Delta T(\theta, \varphi) = \sum_{l,m} a_{l,m} Y_{l,m}(\theta, \varphi).$$

We construct the angular power spectrum as:

$$C_l = \left\langle |a_{lm}|^2 \right\rangle = \frac{1}{2l+1} \sum_{m=-l}^{l} a_{lm}^2$$

which represents the anisotropy at all angular scales θ expressed in terms of multipoles $\ell \approx \pi/\theta$. For a Gaussian distribution, the coefficients C_ℓ contain all the statistical information. Similar decompositions can be made to represent the E and B polarization patterns in their corresponding power spectra. Theory predicts a harmonic structure for the power spectrum, with peaks and valleys resulting from the acoustic oscillations in the plasma. The details of the shape of the power spectrum depend sensitively on the values of the cosmological parameters.

4. The Planck mission

The Planck satellite was successfully launched by an Ariane 5 rocket from the ESA launch pad in Kourou, French Guiana, on 14 May 2009, at 10:12 (local time). The satellite took data uninterruptedly for four years, scanning the sky from an L2 orbit about 1.5 million km away from Earth (Tauber et al., 2010). The telescope, instruments and observing strategy were designed to reach an unprecedented combination of angular resolution (up to a tenth of a degree), sky coverage (100%), wavelength coverage (from 0.3 to 10 mm), sensitivity (one part in a million), calibration accuracy (better than 0.2%).

As discussed earlier, while from Earth we enjoy a relatively clean view of the CMB, local astrophysical emissions contribute to the observed microwave signal and must be accurately removed. The extreme sensitivity of Planck called for precision measurement not only at frequencies dominated by the CMB (70-100 GHz), but also in spectral bands where the foregrounds are strong. Planck observed the sky in nine bands, at frequencies ranging from 30 to 850 GHz. To cover such wide range, two complementary instruments were developed, exploiting state-of-the-art radiometric and bolometric detectors in their best windows of operation, cooled to cryogenic temperatures (up to 0.1 K for the bolometer array)[6]. The two instruments shared the focal plane of a single telescope, an off-axis dual reflector Gregorian system with 1.5m aperture (Figure 4). The ambitious performance of Planck was verified in a demanding ground test campaign before launch, and has been wonderfully confirmed by in-flight data.

Figure 4: Left: picture of the Planck satellite during system ground tests, just before launch. Right: a view of the Planck focal plane, including two integrated instruments: the Low Frequency Instrument, operating in the 30-70 GHz bands, and the High Frequency Instrument, covering the 100-850 GHz range [Courtesy of ESA, ASI, CNES].

[6] The two Planck instruments, LFI, Low Frequency Instrument, and HFI, High Frequency Instrument, are described respectively in (Bersanelli et al., 2010; Lamarre et al., 2010).

5. Precision measurements

In 2018 the Planck Collaboration has released the legacy data in temperature and polarization. Figure 5 shows the temperature full-sky map after removal of the foreground emissions (Planck Collaboration I, 2018). Never was the first light mapped on the whole sky with such precision.

The Planck power spectrum for temperature anisotropy (TT) is displayed in the top panel of Figure 6, which represents the anisotropy power (in units of $\mu\mathrm{K}^2$) conventionally expressed in terms of $\ell(\ell+1)C_\ell/2\pi$ as a function of multipole number $\ell \sim \pi/\theta$. The blue points are the data, the red solid line is the best fit for the base 6-parameters model. Shown are also the residuals. The agreement between data and model is just amazing. The plots in the bottom of Fig. 6 show the power spectra for the polarization E-mode (EE, left) and for the temperature-polarization correlation (TE, right). Note that in the two lower plots, the red curves are not the best fit to the data, but the model for EE and TE spectra using the best-fit 6-parameter model from the TT data. Here one can appreciate the exquisite agreement between the experimental data and the theoretical expectation, as well as the internal consistency between temperature and polarization.

The minimal 6-parameter ΛCDM model used to fit the Planck data assumed a flat geometry, ($\Omega_k = 1 - \Omega_{tot} = 0$); a constant Λ-term for dark energy, i.e., $w_0 = -1, w_a = 0$ for an equation of state $w(a) = w_0 + (1-a)w_a$; standard neutrino parameters (i.e., effective number of relativistic degrees of freedom $N_{eff} = 3.046$, sum of neutrino masses of 0.06 eV, no sterile neutrinos); a simple power law for the of primordial fluctuations, $dn_s/d\ln k = 0$, where k is linear perturbation size; a negligible value of B-modes, parametrized as the ratio r of tensor to scalar modes ($r = 0$); a blackbody temperature for the CMB $T_0 = 2.7255$ K as measured by COBE/FIRAS; a fraction of baryonic mass in helium $Y_P = 0.2477$, as calculated from primordial nucleosynthesis (Hamann et al., 2011); standard amplitude of the lensing power relative to the physical value ($A_L = 1$).

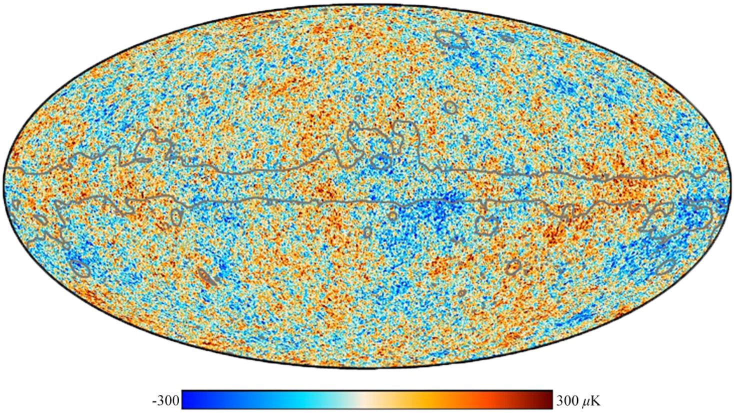

Figure 5: Planck all-sky map of the cosmic microwave background, after subtraction of the galactic and extragalactic foregrounds. Thanks to Planck's nine frequency channels (30-857GHz) and to sophisticated image analysis techniques, the foregrounds emissions were separated with high precision. The sky regions where foreground radiation was larger, mostly in the Galactic plane, is shown by the gray contour (Planck Collaboration I, 2018) [Credits: ESA and the Planck Collaboration].

With these assumptions, the choice of which six free parameters to fit to the data is somewhat arbitrary, as all the others can be derived from those six. For Planck, the free parameters were chosen to be the baryon density, $\Omega_b h^2$; the cold dark matter density, $\Omega_c h^2$; the angular size of the fluctuations, θ_{MC} (times 100); the Thomson scattering optical depth due to reionization, τ; the amplitude and spectral index of the initial fluctuations spectrum, A_S and n_S.

The six basic parameters are derived by fitting the data to the temperature and polarization power spectra. Figure 7 shows contour plots of the constraints on the six parameters obtained independently with the three spectra TT, TE, EE, including large scale polarization, "LowP", as well as the constraints from the combination all spectra. The internal consistency is very good. Table 1 shows in detail the Planck values for the six primary parameters (first block) and the main derived parameters (second block). These results also exploit independent information extracted from the Planck data on the effect of weak gravitational lensing on the CMB (Planck Collaboration VIII, 2018). Of the six primary parameters shown in Table 1, five are measured to better than 1%. The errorbars are somewhat further reduced when the Planck data are combined with external data sets, particularly from baryonic acoustic oscillations (Planck Collaboration VI, 2018).

The Planck results indicate a contribution to the energy density from baryonic matter of 4.9%, from dark matter of 26.5%, and the remaining 68.5% is ascribed to dark energy. This means that less than 5% of the universe is made of stuff that we understand in terms of known physics. The Hubble constant is found to be 67.4 ± 0.5 km s^{-1}Mpc^{-1}, indicating a somewhat lower value than previous estimates based on more traditional methods. The combination of Hubble constant and of density parameters yield an estimate of the age of the universe of 13.8 billion years, with the amazing precision of 0.3%.

Extending the analysis beyond the base 6-parameters model is done by relaxing the assumed fixed values of extra parameters. This

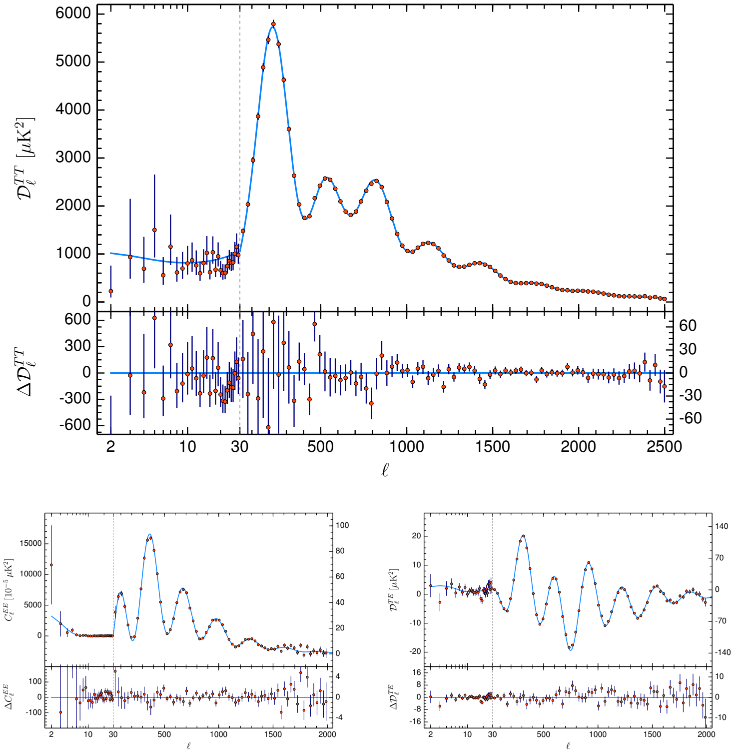

Figure 6: Planck angular power spectra. Top panel: temperature anisotropies; Bottom left: polarization E-mode; Bottom right: correlation of T and E-mode (Planck Collaboration VI, 2018). The horizontal axis is the multipole number, inversely proportional to the angular scale (left to right: 180 degrees to 7 arcmin). The vertical axis is the anisotropy power in unites of μK^2 (see text) [Credits: ESA and the Planck Collaboration].

way, stringent limits are placed to the sum of all neutrino masses, < 0.24 eV, tighter than any previous experiment. The Planck data combined with other data sets, especially those from large galaxy

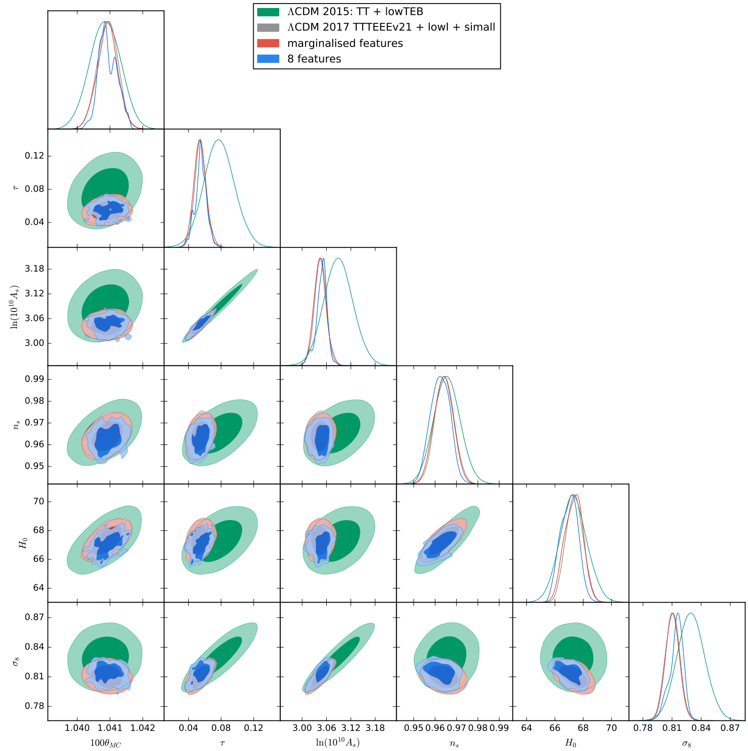

Figure 7: Constraints from Planck data on the six base cosmological parameters of the ΛCDM model from temperature and polarization data (Planck Collaboration VI, 2018) [Credits: ESA and the Planck Collaboration].

surveys, set tight limits on the curvature of the universe sub percent level. We seem to live in a highly Euclidean universe. The spectral index of the primordial perturbations is found to be $n_S = 0.965 \pm 0.004$, i.e. close to, but significantly less than, unity. These two latter results are consistent with the expectations of most popular inflationary scenarios. The signature of primordial gravitational waves is measured by the parameter r, the ratio of tensor perturbations (producing the B-mode polarization) to density perturbations. The Planck data place an upper $r < 0.09$ (95% confidence level), which implies an upper limit for the energy scale of standard inflation of 1.9×10^{16} GeV. An analysis combining Bicep2 and KEK with Planck data yields $r < 0.07$ at 95% confidence level (Keck Array and BICEP2 Collaborations, 2016). These limits seem to rule out the simplest forms of inflation models, a situation that has increased the motivation to consider alternative approaches to the inflation scenario (see e.g. Ijjas, Steinhardt and Loeb, 2013).

Primary ΛCDM parameters

Parameter		Planck 2018
$\Omega_b h^2$	*Baryon density today* $^{(a,\ b)}$	0.02237 ± 0.00015
$\Omega_c h^2$	*Cold dark matter density today* $^{(a,\ b)}$	0.1200 ± 0.0012
$100\theta_{MC}$	*Angular scale of sound horizon at last scattering*	1.04092 ± 0.00031
τ	*Thomson scattering optical depth due to reionization*	0.0544 ± 0.0073
$ln(10^{10} A_S)$	*Power of primordial perturbations*	3.044 ± 0.014
n_S	*Spectral index of primordial perturbations*	0.9649 ± 0.0042

DERIVED PARAMETERS

Parameter		Planck 2018
H_0	*Hubble constant*, km s^{-1} Mpc^{-1}	67.36 ± 0.54
Ω_Λ	*Dark energy density today* $^{(a)}$	0.6847 ± 0.073
Ω_m	*Dark matter density today* $^{(a)}$	0.3153 ± 0.073
σ_8	*RMS matter fluctuations today (on scale 8/h Mpc)*	0.8111 ± 0.0060
z_{re}	*Redshift at which the universe is half re-ionized*	7.67 ± 0.73
z_{eq}	*Redshift of matter-radiation equality*	3402 ± 26
t_U	*Age of the universe*, Gyr	13.797 ± 0.023

EXTENSIONS OF BASE 6-PARAMETERS MODEL

Parameter		Planck 2018
Ω_K	*Curvature parameter today* $^{(a)}$, $\Omega_{tot} = 1 - \Omega_K$	-0.0096 ± 0.0061
$\sum m_v$	*Sum of neutrino masses, eV*	< 0.241
N_{eff}	*Effective number of neutrino species*	$2.89^{+0.36}_{-0.38}$
$r_{0.002}$	*Tensor to scalar ratio at a scale* $k_0 = 0.002$ Mpc^{-1}	< 0.101

(a) In units of critical density, $3H_0^2/8\pi G$.

(b) Here $h = H_0/(100$ km s^{-1} Mpc$^{-1})$.

Table 1: The six parameters of the ΛCDM (on top) and derived parameters from the Planck legacy release (Planck Collaboration I, 2018). The parameters are derived from the combined analysis of temperature, polarization and lensing data.

6. Conclusions

The cosmic microwave background is a unique window into the early universe. The CMB photons reach us from a region of space-time which is both the outer rim of our observable universe and the image of a small, hot, young universe. This situation has remarkable analogy with Dante's medieval cosmos, though of course in a very different context. Accurate, full-sky imaging of the CMB gives a snapshot of the gravitational seeds from which galaxies and all cosmic structure formed. Recent measurement of the CMB temperature and polarization anisotropy succeeded in constraining to great precision the main fundamental parameters of cosmology, such as those describing the density of different kinds of matter and energy in the universe, the overall geometry of space, the dynamics of cosmic expansion, the mass and number of species of neutrinos, the age of the universe. Polarization measurement also probe processes occurring in the very first tiny fraction of a second of the big bang at energies far greater than any conceivable terrestrial experiment.

The image of the cosmos emerging in contemporary cosmology is characterized by a combination of simplicity and mystery. The level of agreement shown in Figure 6 is truly astonishing. It means that the data are very well described by the simplest standard cosmological model, in which just six numbers are sufficient to capture the overall state of the early universe to high precision. This is encouraging for our ambition to reach a synthetic description of the properties of the universe, and it seems to indicate that we are on the right track. On the other hand, several fundamental questions remain open. These same data are telling us that we have no clue on the physical nature of as much as 95% of what exists in the universe. Also, the very early universe remains mostly uncharted territory. Inflation is a promising path, but it still awaits confirmation. The Planck results rule out classic inflation models and less natural potentials must be considered. Furthermore, inflation is not a complete theory and it may face conceptual difficulties (Steinhardt, 2011; Ijjas, Steinhardt and Loeb, 2014). Our experiments will continue to search for B-mode signatures of primordial gravitational waves, and their detection would represent an extraordinary discovery. However, the field is open and we should maintain an open-minded view on what we might find or not find in the data.

The generous scientific payoff that CMB observations have delivered in the past 50 years does not seem to be over, and more breakthroughs can be hoped-for in the next decade. Much technological development has occurred since the Planck instruments were frozen. A new generation of experiments is being developed and deployed in selected high-quality ground-based sites (such as South Pole, Atacama, Tenerife), particularly to probe B-mode polarization. Studies for a future fourth generation CMB space mission are ongoing, such as the JAXA's LiteBIRD project. It will be interesting to see whether our favorable astronomical location in the Milky Way will assist us also in the next stage of precision measurements, as we move from the micro-Kelvin to the nano-Kelvin regime.

Our recent CMB results indicate that the early universe was an amazingly simple place, nearly featureless and well described by only a few numbers. Probably nobody would have bet, if watching the scene back then, on a future as rich and interesting as the one that we experience today. And yet here we are, 13.8 billion years later, to tell the marvelous story.

Bibliography

Bennett, C.L. et al., 2003. First-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: preliminary maps and basic results. *The Astrophysical Journal Supplement Series* [Online], 148, pp.1–27. Available at: https://doi.org/10.1086/377253 [Accessed 28 November 2018].

Bersanelli, M., 2018. *From Dante's Universe to Contemporary Cosmology [in press]*. Milano: Istituto Lombardo Accademia di Scienze e Lettere.

Bersanelli, M. et al., 2010. Planck pre-launch status: design and description of the Low Frequency Instrument. *Astronomy & Astrophysics* [Online], 520, A4. Available at: https://doi.org/10.1051/0004-6361/200912853 [Accessed 28 November 2018].

Dicke, R.H., Peebles, P.J.E., Roll, P.G. and Wilkinson, D.T., 1965. Cosmic black-body radiation. *The Astrophysical Journal* [Online], 142, pp.414–419. Available at: https://doi.org/10.1086/148306 [Accessed 28 November 2018].

Fixsen, D.J., 2009. The temperature of the cosmic microwave background. *The Astrophysical Journal* [Online], 707, pp.916–920. Available at: https://doi.org/10.1088/0004-637X/707/2/916 [Accessed 28 November 2018].

Guth, A.H., 1997. *The Inflationary Universe: the Quest for a New Theory of Cosmic Origins*. OCLC: 301573086. Reading, Mass.: Addison-Wesley.

Hamann, J., Hannestad, S., Raffelt, G.G. and Wong, Y.Y.Y., 2011. Sterile neutrinos with eV masses in cosmology – How disfavoured exactly? *Journal of Cosmology and Astroparticle Physics* [Online], 2011(09), p.034. Available at: https://doi.org/10.1088/1475-7516/2011/09/034 [Accessed 28 November 2018].

Harrison, E.R., 1981. *Cosmology: the Science of the Universe*. Vol. 2000. Cambridge: Cambridge University Press.

Hinshaw, G. et al., 2007. Three-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: temperature analysis. *The Astrophysical Journal Supplement Series* [Online], 170, pp.288–334. Available at: https://doi.org/10.1086/513698 [Accessed 28 November 2018].

Ijjas, A., Steinhardt, P.J. and Loeb, A., 2014. Inflationary schism. *Physics Letters B* [Online], 736, pp.142–146. Available at: https://doi.org/10.1016/j.physletb.2014.07.012 [Accessed 28 November 2018].

Ijjas, A., Steinhardt, P.J. and Loeb, A., 2013. Inflationary paradigm in trouble after Planck2013. *Physics Letters, Section B: Nuclear, Elementary Particle and High-Energy Physics* [Online], 723(4-5), pp.261–266. Available at: https://doi.org/10.1016/j.physletb.2013.05.023 [Accessed 28 November 2018].

Keck Array and BICEP2 Collaborations, 2016. Improved constraints on cosmology and foregrounds from BICEP2 and Keck Array cosmic microwave background data with inclusion of 95 GHz band. *Physical Review Letters* [Online], 116(3), p.031302. Available at: https://doi.org/10.1103/PhysRevLett.116.031302 [Accessed 28 November 2018].

Lamarre, J.-M. et al., 2010. Planck pre-launch status: the HFI instrument, from specification to actual performance. *Astronomy & Astrophysics* [Online], 520, A9. Available at: https://doi.org/10.1051/0004-6361/200912975 [Accessed 28 November 2018].

Leitch, E.M. et al., 2002. Measurement of polarization with the Degree Angular Scale Interferometer. *Nature* [Online], 420(6917), pp.763–771. Available at: https://doi.org/10.1038/nature01271 [Accessed 28 November 2018].

Mather, J.C. et al., 1994. Measurement of the cosmic microwave background spectrum by the COBE FIRAS instrument. *The Astrophysical Journal* [Online], 420, pp.439–444. Available at: https://doi.org/10.1086/173574 [Accessed 28 November 2018].

Peebles, P., Page Jr, L. and Partridge, R.B., 2009. *Finding the Big Bang*. Cambridge: Cambridge University Press.

Penzias, A.A. and Wilson, R.W., 1965. A measurement of excess antenna temperature at 4080 Mc/s. *The Astrophysical Journal* [Online], 142, pp.419–421. Available at: https://doi.org/10.1086/148307 [Accessed 28 November 2018].

Peterson, M.A., 1979. Dante and the 3-sphere. *American Journal of Physics* [Online], 47, pp.1031–1035. Available at: https://doi.org/10.1119/1.11968 [Accessed 28 November 2018].

Planck Collaboration I, 2018. Planck 2018 results. I. Overview and the cosmological legacy of Planck [in press]. *arXiv:1807.06205 [astro-ph]* [Online]. Available at: <http://arxiv.org/abs/1807.06205> [Accessed 28 November 2018].

Planck Collaboration VI, 2018. Planck 2018 results. VI. Cosmological parameters [in press]. *arXiv:1807.06209 [astro-ph]* [Online]. Available at: <http://arxiv.org/abs/1807.06209> [Accessed 28 November 2018].

Planck Collaboration VIII, 2018. Planck 2018 results. VIII. Gravitational lensing [in press]. *arXiv:1807.06210 [astro-ph]* [Online]. Available at: <http://arxiv.org/abs/1807.06210> [Accessed 28 November 2018].

Smoot, G.F. et al., 1992. Structure in the COBE differential microwave radiometer first-year maps. *The Astrophysical Journal Letters* [Online], 396, pp.L1–L5. Available at: https://doi.org/10.1086/186504 [Accessed 28 November 2018].

Speiser, A., 1925. *Klassische Stücke der Mathematik*, *Veröffentlichungen der Schweizerischen Mathematischen Gesellschaft* 2. Zürich – Leipzig: Verlag Orell Füssli.

Steinhardt, P.J., 2011. The inflation debate. *Scientific American* [Online], 304(4), pp.36–43. Available at: https://doi.org/10.1038/scientificamerican0411-36 [Accessed 28 November 2018].

Tauber, J.A. et al., 2010. Planck pre-launch status: the Planck mission. *Astronomy & Astrophysics* [Online], 520, A1. Available at: https://doi.org/10.1051/0004-6361/200912983 [Accessed 28 November 2018].