New physics from the Cosmic Microwave Background

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Abstract. I review the present status of the Cosmic Microwave Background, with some emphasis on the current and future implications for particle physics.

Keywords: CMB – phenomenology – speculation

1. Background

Figure 1 gives an overview of information on background radiation in the Universe. The reason to plot $\nu I_\nu$ is so that it is possible to read off the relative contributions to total energy density. What can be seen is that the Cosmic Microwave Background (CMB) is by far the dominant background. The CMB corresponds to an energy density of $0.260 \text{ eV cm}^{-3}$, or a number density of $410 \text{ cm}^{-3}$, corresponding to about 2 billion photons per baryon in the Universe today. On the figure, the next biggest background – almost two orders of magnitude down in energy contribution – is in the far-IR/sub-mm part of the spectrum, and believed to come from distant, dusty, star-forming galaxies. A little below that is the near-IR/optical background, coming from the sum of the emission of all the stars in all the galaxies we can observe. Then much lower are the X-ray and $\gamma$-ray backgrounds, which come predominantly from active galactic nuclei.

Apart from the CMB, there is no evidence for background emission arising from anything other than known sources of radiation: stars, gas and dust within galaxies. In other words, there is no reason to believe that decaying particles, for example, distributed throughout the Universe,

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Figure 1. A compilation of recent constraints on extragalactic diffuse background radiation. In terms of total energy the CMB dominates, with the Far-Infrared and Optical Backgrounds about a factor of 100 lower. These data are based upon the older compilation of primarily from Ressell & Turner 1990 [1], supplemented with more recent data from: Smoot 1997 [2] for the CMB; Lagache et al 1999 [3] and Hauser et al 1998 [4] for the FIB; Leinert et al 1998 [5] for a near-IR to near-UV compilation; Dwek & Arendt 1998 [6] for the near-IR; Pozzetti et al 1998 [7] for the optical; Miyaji et al 1998 [8] and Gendreau et al 1995 [9] for the X-ray; and Sreekumar et al 1998 [10], Kappadath et al 1999 [11] and Watanabe [12] for the γ-ray. In the colour version lower limits are shown in red and upper limits in blue.
are contributing much to the background, and hence these sorts of data can place constraints on exotic particles (e.g. \[1\]). The CMB is different, however. Its spectral shape is spectacularly well-fit by a blackbody \[13, 14, 3\], over more than 4 decades in frequency. The current best estimate of the CMB temperature is

$$T_0 = 2.725 \pm 0.001 \text{ Kelvin}$$  \hspace{1cm} (1)  

\[15\]. The fact that the CMB is such a good blackbody is one of the pillars of the standard Big Bang model. The argument is that, since we can’t even make such a good blackbody in the lab, the CMB needs to have originated from something in extraordinarily good thermal equilibrium. The only known source is the entire Universe, during an earlier epoch when it was very much hotter and denser. Together with the Hubble law for distant galaxies, this leads to a robust model in which the Universe used to be hot and dense, and has been cooling and expanding since then.

Since we know that the Universe consists mainly of hydrogen, we can calculate (see \[16\] for a recent update) that the Universe was ionized when it was hotter than about 4,000 K (a lower temperature than you might have first guessed, because of the high photon-to-baryon ratio). Since the radiation redshifts just like \(T \propto (1 + z)\), then that means the Universe recombined at \(z \approx 1500\). This was the time when the radiation last interacted with the matter (through electron scattering), and most CMB photons have been travelling freely since then. In models with typical parameters, this epoch corresponds to a time of around 300,000 years.

The spectrum is thermalised (by double Compton and Bremsstrahlung) for times earlier than about 1 year, corresponding to \(z \sim 10^7\). Hence particle decays, or other energy emitting processes, occurring over the redshift range \(10^3 < z < 10^7\), could leave an observable signature on the CMB spectrum (see e.g. \[17\]).

Although all measurements are currently only upper limits, there is some prospect of detections of spectral distortions from planned spectral experiments \[18\]. For example, at low frequencies it seems feasible to detect Bremsstrahlung emission from the reionized gas in the inter-galactic medium at moderate redshifts \[19\]. However, progress in constraining other realistic physical effects will require considerably greater improvements in experimental sensitivity.

As well as distortions to the spectrum, the CMB also contains cosmological information in the variations in temperature across the sky \[20\].

\[2\] This process is always called recombination, even although in the cosmological context the atoms begin by being uncombined, and hence the process is really combination. For particle physicists who feel the corners of their mouths lifting here, let me point out that this is not too dissimilar to the talk of symmetry restoration in the early Universe, which only makes literal sense if time runs backwards.
After the detection of CMB anisotropy by the COBE satellite in 1992 [21], attention has been focussed almost exclusively on these anisotropies. This is partly because it became clear that detection was easily within reach of state-of-the-art detectors, but also because theoretical calculation showed that precise measurements of the anisotropy power spectrum would provide detailed information about fundamental cosmological parameters [22].

Since COBE there have been around 20 separate experiments which have detected temperature fluctuations which are most likely to be primordial. These are summarized in Figure 2. Here the x-axis is the spherical harmonic multipole, ℓ. The temperature fluctuation field on the sky can be decomposed into an orthogonal set of modes:

\[ \frac{\Delta T}{T} (\theta, \phi) = \sum_{\ell, m} a_{\ell m} Y_{\ell m}(\theta, \phi). \]  

Since there is no preferred direction on the sky (e.g. [23]) the individual ms are irrelevant, and so the important information is contained in the power spectrum

\[ C_\ell \equiv \langle |a_{\ell m}|^2 \rangle. \]  

Indeed if the perturbations are Gaussian, then this contains all the information. The conventional amplitude of the quadrupole is given as

\[ \frac{Q^2}{T_0^2} \equiv \frac{\sum_m |a_{\ell m}|^2}{4\pi} = \frac{5C_2}{4\pi}. \]  

A ‘flat’ spectrum means one in which \( \ell(\ell + 1)C_\ell = \text{constant} \), and we can therefore define that constant in terms of the expectation value for the equivalent quadrupole \( Q_{\text{flat}} \) – which is what is plotted as the y-axis in Figure 2.

Each experiment quotes one (or in the best cases several) measures of power over a range of multipoles, and these can be quoted as ‘band powers’ or equivalent amplitudes of a flat power spectrum through some ‘window function’. The horizontal bars on the points are an indication of the widths of these window functions.

2. What do we know?

There are a number of things to note from Figure 2 [24]:

• The plot has become very crowded!
• The overall detection of anisotropy is at the \( \simeq 40\sigma \) level.
Most of the experiments published to date. See Smoot & Scott (1997) for full references, supplemented with more recent results from: OVRO Ring [25], QMAP [26], MAT TOCO [27], CAT [28], Python V [29] and Viper [30]. The error bars (these are 1σ except for the upper limits which are 95%) have generally been symmetrised for clarity, and calibration uncertainties are included in most cases. The horizontal bars represent the widths of the experimental window functions. The dotted line is the flat power spectrum which best fits the COBE data alone. The dashed curve is the prediction from the vanilla-flavoured standard Cold Dark Matter model.
• A flat power spectrum (horizontal dotted line) is a bad fit, at about the 15σ level.
• There is clear evidence for a peak at ℓ ~ 200.

What do we learn from this? First of all, it looks like our basic paradigm – to describe the large scale properties of the Universe, and the formation of structure within it – are in good shape. The prediction from the ‘straw man’ model, standard Cold Dark Matter (sCDM) is shown by the dashed line in Figure 2. The point is that this model, which contains parameters which are all fixed at very round numbers, has the right general character. And it is easy to find models which fit the data much better, by tuning some of those parameters.

What we already know can be split (artificially) into 3 areas: astrophysics, cosmology and particle physics, each of which I will now discuss in turn. For more details refer to the review article by Lawrence et al. (1999) [24].

2.1. Astrophysics

Before the COBE detection, there had been about 25 years of quoted upper limits to CMB anisotropy. There was much talk in the literature about how new paradigms would be required if COBE returned yet stronger upper limits. But in fact the detection was just at the right level for gravity alone to have grown the structure from amplitudes of $\sim 10^{-5}$ at $z \sim 1000$ to the non-linear structures we see today. This is easy to arrange for models in which the Universe is dominated by non-baryonic dark matter, and with adiabatic perturbations. Thus, probably the most important thing to come out of the COBE anisotropy measurements (apart from the general good news that we are on the right track!) is the realization that

Gravitational instability in a dark matter dominated universe grew today’s structure

This ‘fact’, arising from the CMB, has added to the Big Bang paradigm, so that the picture is of a hot expanding Universe, which at early times contained small amplitude density perturbations. The obvious next question is where those perturbations came from – an issue we shall return to in a minute.

Meanwhile, there are a few other things that the current suite of CMB measurements tells us. First of all, it is pleasing that the approximate scale of the peak (apparent in the binned plot, Figure 3) is just where it is theoretically predicted in simple models. This acoustic peak corresponds to the length scale which a sound wave can travel at the time of recombination, projected onto the sky, and was contained in papers at least as early as
Figure 3. The result of binning the data in the previous figure. More precisely, what was done was to split the multipoles into 16 bins between $\ell = 2$ and $\ell = 1000$, and to weight each experiment by the fraction of the window in each bin. The precise height of the peak depends to some extent on the choice of bins, on details of the window functions used, and on the weights given to individual experiments. The points here are not uncorrelated, but provide a reasonable visual impression of the current data – more sophisticated treatments (e.g. [32] give similar results). The solid line is a $\Lambda$-dominated CDM model, with parameters which are consistent with most current cosmological constraints.
Doroshkevich, Sunyaev & Zel’dovich (1978) [31]. The position in angle is also a good test for the geometry of the Universe, since it comes from the projection of a fixed physical scale onto the sky.

We know (from the lack of complete absorption shortwards of the Lyman edge in distant quasars) that most of the material in the nearby Universe is ionized, out to redshifts $z > 5$. Whether the Universe reionized at $z \sim 10$ or $z \sim 1000$ is, however, not obvious. But, very early reionization would lead to the erasing of the small-scale CMB anisotropies, which patently has not occurred. Hence we can infer that

The Universe remained neutral until $z \lesssim 50$

(see e.g. [33]).

2.2. Cosmology

Let us imagine for the sake of this section, that ‘cosmology’ is synonymous with the search for the values of a number of parameters which describe the properties of the Universe.

Figure 3 appears to show that

The CMB power spectrum peaks at $150 \lesssim \ell \lesssim 350$,

avoiding any detailed statistical arguments here, and just sticking to round numbers (and remembering that there are tight upper limits at higher values of $\ell$, so that the power spectrum really does have to come down again). Since the standard CDM model has the main peak at $\ell \simeq 220$, and it is pushed to smaller scales in open models, then it is hard for $\Omega_{\text{tot}}$ to be less than, say, 0.3. Rigorous studies (e.g. [34]) arrive at similar conclusions.

The height of the peak is somewhat higher than predicted for sCDM, but entirely consistent with several variants. Currently popular models with a cosmological constant tend to provide perfectly good fits to the CMB (in addition to large-scale clustering of galaxies and the supernovae results [35]). The curve plotted in Figure 3, shows one such flat model with $\Omega_{\Lambda} = 0.6$ and a Hubble constant of $70\,\text{km}\,\text{s}^{-1}\text{Mpc}^{-1}$ [36].

Since the height of the first peak depends on a combination of parameters, then exactly what quantities are constrained depends on the parameter space being searched, as well as on the choice of additional constraints. Currently it is possible to constrain the matter density $\Omega_{M}$ to $\sim \pm 0.1$ from the peak height, but that depends sensitively on the assumptions used. All this is expected to change as better data come in.

3 Rather than vanilla CDM you can have a slightly different flavour, or some chocolate sprinkles, or maybe a cherry on top.
The basic thing to take away here is that models with adiabatic-type (i.e. where you perturb the matter and radiation at the same time in order to keep the entropy fixed) perturbations have the right kind of character. On the other hand isocurvature-type models (where the matter and radiation get equal and opposite perturbations, so that the local curvature is unperturbed) tend to look poor – generically they have a ‘shoulder’ rather than a first peak, and then the highest peak is at much smaller scale (see e.g. [37]). While there are some loop-holes, it seems difficult to get isocurvature models to fit the current data.

2.3. Particle physics

Let me briefly discuss some particle physics implications. For a more complete discussion see the recent review by Kamionkowski & Kosowsky [38].

The best-fitting models for the CMB, in conjunction with other cosmological constraints, seem to imply that there may be a positive cosmological constant, or other form of matter which behaves in a similar way. Since ‘extraordinary claims require extraordinary evidence’ I think it is premature to say that the energy density of the vacuum has now been measured. But since $\Omega_\Lambda \simeq 0.6$ really is the best fit at the moment, it is worth exploring this more fully. The implications for particle physics models are obviously profound.

The CMB has little to say about the neutrino, unless its mass is high enough that free-streaming of the dark matter particles is important (which is only the case for $m_\nu \gtrsim$ few eV, see [39] for discussion). But the CMB certainly requires (again much more strongly when other constraints are taken into account) that most of the matter content is in some cold dark, non-baryonic form – and some new particle is the favoured candidate. Whether it is the axion, the lightest supersymmetric particle, or something else, remains to be seen.

There are many other constraints on particle physics which are beginning to be discussed. The basic idea is that the Universe couldn’t have been too crazy at $z \sim 1000$, otherwise the microwave sky would appear very different. Already there have been limits placed on: strong primordial magnetic fields; large domains of anti-matter; large lepton asymmetry; particle decays; and early phase transitions. At the moment the limits are not too severe on things that anyone believed in the first place, but this will certainly change as the data improve.

I’m not sure how much this belongs in the particle physics section, but there are various models in which the large-scale structure of the Universe is non-trivial, either in terms of global rotation or topology. If these are too extreme they lead to detectable patterns on the CMB sky [40]. In the simplest models with strange topology, the scale has to be so close to the
Hubble scale as to be hardly worth considering [41], although in models with hyperbolic geometry things are much less clear [42]. But of course, open models are not currently in vogue. In any case the conclusion is that

*The large-scale structure of spacetime appears to be simple.*

2.3.1. *Inflation.* Most people working in the field which is sometimes referred to as ‘CMB phenomenology’ are currently struggling with the same question, in one form or another (e.g. [43]): how does one confront the concept of Inflation with the concept conventionally known as Proof?

It seems clear that we are now in a position to say something beyond the Big Bang paradigm. The CMB led us to accept that the Universe used to be hotter and denser, and more recently to the conclusion that structure built up through gravitational instability. Now it appears that we are learning something further, something about the origin of the perturbations themselves. But just exactly what that next step is, and how to phrase it, is altogether less clear. For lack of anything better, let me phrase my own current belief, which I challenge anyone to disagree with:

*Something like Inflation is something like proven*

Of course the interpretation of this statement depends on the exact definition of the two crucial words. I’m sure that I don’t know what I mean by ‘proof’. But by ‘inflation’ I mean some mechanism which gave rise to a roughly scale-invariant spectrum of adiabatic perturbations, over a wide range of scales, including those which are apparently acausal. The only causal way we know of to do this is to have the scale factor accelerate ($\ddot{a} > 0$) at some time in the early history of the Universe [44]. And we can argue about whether something that achieves the same end result is just isomorphic to inflation, even if interpreted differently. ‘Inflation’ does not necessarily carry with it the extra baggage of an inflaton potential etc. – although hopefully the connection with particle physics would follow later.

It used to be that discussions of inflation focused on the number of e-foldings required to solve horizon, flatness, entropy and monopole problems. However, at the present time the paramount concern is making those darned density perturbations. And inflation gives you a mechanism to do that, for free! It appears that we are learning that the Universe has inflation-like ‘initial conditions’. Time will tell whether that means that the Universe was once dominated by some vacuum energy density, and whether we can learn details about particle physics at ultra-high energies. The promise of the CMB is that it provides a way of probing density perturbations while they were still in the linear regime (i.e. simple). Thus we may be able to learn details of how the perturbations were generated which may lead to direct information about physics at energies at the GUT scale, or even the Planck scale.
2.3.2. Defects. Since I had many discussions at this meeting about alternatives to inflation, let me dwell a little on that subject here. The only real competitor to inflation has been any one of various field ordering mechanisms or topological defect models. Generically these give larger CMB anisotropies (from the so-called integrated Sachs-Wolfe effect) for the same density perturbation amplitudes\(^4\). The power spectra of galaxy perturbations, or even the underlying dark matter fluctuations, are notoriously complicated to calculate – nevertheless there seems little evidence that the observed power spectrum can be easily reproduced in these sorts of models. Moreover, there now seems to be some consensus in the view that generic defect models produce at most one (broad) peak in the CMB power spectrum\(^5\) and in a place which tends to give a poor fit to current data.

The status of defects vs. the Universe can be summarized in the following three points. Defect models tend to give

- the wrong matter power spectrum;
- the wrong CMB power spectrum;
- the wrong normalization of matter relative to CMB.

But apart from that, these models seem to work fine!

There is certainly a strong motivation for working on such models simply from the point of view that they are cool. Some of the required mathematics is interesting in its own right and some of the numerical calculations are challenging. It would be neat if the Universe was full of a network of cosmic strings, containing within them trapped regions of GUT-scale physics, and thrashing around at near the speed of light. To put it another way, who wouldn’t sometimes rather be Captain Jean-Luc Picard? But ultimately it doesn’t matter what sort of Universe we would like to live in\(^5\); we are stuck with this particular one, and we are learning a great deal about its properties. Details of the structure within our Universe seem relatively easy to fit with inflationary-type models, and considerably harder with defect-type models.

Which is not to say that defects are not important in other branches of physics – or even perhaps for other purposes in the early Universe – but at this point they seem to hold little promise as a method of forming structure.

\(^4\) This is basically because of their similarity to isocurvature models; adiabatic (i.e. inflationary) models, on the other hand, give the correct value to a factor of 2, without really breaking sweat.

\(^5\) My own sense of humour makes models with say \(\Omega_{\text{tot}} = 1.1\) sound pretty appealing!
2.3.3. Other paradigms? There is of course an argument in favour of investigating other possibilities, at least until such time as inflation has been more directly tested. While the current suite of defect models do not look very promising, there is always the possibility of a more attractive model lying around corner.

New ideas from particle physics also have the potential for providing different mechanisms for structure formation. Exactly what will come out of string theory, large extra dimensions and broken Lorentz invariance remains to be seen. It will be interesting to see how generic the basic inflationary predictions are, and whether new twists on high energy physics carry with them new testable predictions.

3. Future experiments

More information can be found in recent reviews (e.g. [46, 18]). Here I give a very brief summary.

The next generation of CMB balloon experiments are expected to return data of much higher quality (and quantity). The new results from BOOMERanG [17] (as well as MSAM, MAXIMA and others) are eagerly awaited. BOOMERanG ‘98 was the first long-duration balloon flight, and by all accounts was staggeringly successful. Three immediate questions are expected to be addressed by this new data-set: do the currently favoured $\Lambda$-dominated cosmologies continue to be a good fit; what is the precise location of the first peak; and is there any evidence for other peaks. This last point is perhaps the most important. Detection of oscillations in the power spectrum, with tight constraints on the peak spacings, will be a very firm test of the inflationary paradigm [48].

The adiabatic, apparently acausal perturbations, generated during inflation, give a series of peaks in the ratio $1 : 2 : 3 : \cdots$ in $\ell$-space. On the other hand, causal, isocurvature perturbations naturally give rise to peaks in the ratio $1 : 3 : 5 : \cdots$. So detection of a second peak at roughly half the angular scale of the first, will be a very large step towards ‘proving inflation’. Failure to observe this will, of course, be even more exciting, since it will demand an entirely new paradigm.

In the short term there are also at least three new interferometer projects (e.g. [49]): DASI at the South Pole, CBI in Chile and the VSA in Tenerife. All of these are nearing completion and the improvement in the available data is expected to increase even more when they return data within the next year or two.

Another direction being pursued from the ground is CMB polarization – see [50] for experimental details and [51] for a theory primer. The CMB sky is naturally polarized at the few percent level (the result of the quadrupole
term in Compton scattering together with a slightly anisotropic radiation field at \( z \sim 1000 \)). Measuring the \( \sim \mu \text{K} \) signals will be very challenging, but can provide information beyond that contained in the temperature anisotropies alone. Since polarization is such a strong prediction, it better be there, otherwise our whole picture has to change! Furthermore, we can more definitively separate any gravity wave contribution in the CMB (if it is measurable\(^5\)), thus limiting the energy scale of inflation. Large-angle polarization can also constrain the reionization epoch, and details of the polarization power spectrum are a direct probe of physics around the time of last scattering. This is all in addition to the fact that polarization simply gives extra information to better constrain parameters (and to break degeneracies between some combinations of parameters).

4. MAP and Planck

Two satellite missions are currently planned to study the CMB from space, where the whole sky can be imaged, far from the complicating effects of the atmosphere. The NASA Microwave Anisotropy Probe (MAP\(^5\)) is due for launch in November 2000. It will travel to the Earth-Sun outer Lagrange point, L2, where it will map the sky at 5 frequencies between 22 and 90 GHz, reaching to \( \ell \sim 800 \) in the power spectrum. The careful control of systematics possible with an extended space mission means that MAP should represent a very large improvement over the data available from the Earth-based experiments.

The ESA mission Planck can be thought of as the third generation CMB satellite, mapping at 9 separate frequencies between 30 and 850 GHz, with both radiometer and bolometer technologies, and measuring the \( C_\ell \)s to beyond \( \ell \) of 2000. Thus Planck is expected to measure essentially all of the primordial CMB power spectrum (see Figure 4), and cover all the frequencies required to measure and remove the foreground signals. The Planck data set should enable cosmological parameters to be constrained with exquisite precision – or, to put it another way, the power spectrum should be measured at a level of several million \( \sigma \). In addition Planck will measure the polarization (and cross-correlation with temperature) power spectra, providing even more information.

In terms of particle physics, there will be constraints on anything which could potentially affect the anisotropies. This is just like Big Bang Nucleosynthesis constraining strange things occurring at \( \sim \text{MeV} \) energies, or \( \sim \text{minute} \) timescales. There have already been many studies (too many to list in detail) estimating how well various things could be limited by Planck data. These include: variation of fundamental constants; decaying particles; \( \Lambda \), Quintessence, rolling scalar fields, Dark Energy, etc. equation
Figure 4. An estimate for how well the power spectrum might be measured by Planck. This is a realization of a CDM power spectrum, assuming the Planck instrumental sensitivity over two thirds of the sky. Planck should supply us with essentially cosmic-variance limited information on all the angular scales relevant to primary anisotropies, over the full range of relevant frequencies.
of state; alternative gravity models; parity violation; extra relativistic
degrees of freedom; and just about anything else you can think of which isn’t
already ruled out.

Certainly cosmological parameters will be constrained. And definitely
some messy astrophysical details will be uncovered (in the foregrounds, as
well as through some weak processing effects occurring between \( z = 0 \) and
1000). And whatever the basic paradigm, there will surely be some clues to
fundamental physics lurking in there, since the CMB anisotropies provide
the cleanest information about the initial conditions and the largest scale
properties of the Universe. What is therefore clear is that

\[ \text{We will learn a great deal about cosmology, astrophysics and particle} \]
\[ \text{physics from MAP and Planck} \]

5. Conclusions

The main points are highlighted in italics throughout. We are beginning
to learn the answers to some fundamental questions, using information
contained in CMB anisotropy data. With future experiments, and the MAP
and Planck satellites in particular, we should expect to learn vastly more
in the coming years about astrophysics, cosmology and particle physics.

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lessly concentrated on my own work – see the original papers for more
comprehensive references. I am also grateful to the members of CITA for
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