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What Will We Learn From the CMB?

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1. Introduction

Within the next decade, experiments measuring the anisotropies in the cosmic microwave background (CMB) will add greatly to our knowledge of the universe. There are dozens of experiments scheduled to take data over the next several years, capped by the satellite missions of NASA (MAP) [1] and ESA (PLANCK) [2]. What will we learn from these experiments? I argue that the potential pay-off is immense: We are quite likely to determine cosmological parameters to unprecedented accuracy. This will provide key information about the theory of structure formation and even about the physics behind inflation. If the experiments succeed, can anything spoil this pay-off? I focus on three possible spoilers – foregrounds, reionization, and defect models – and argue that we have every reason to be optimistic.

2. The Potential

It is customary to characterize CMB anisotropies by the power spectrum, the C_l's. These are the average of the square of coefficients of the temperature field decomposed into a sum over spherical harmonics. Large scale anisotropies are characterized by the C_l's at small l (e.g. $l = 2$ is the quadrupole), while small scale anisotropies are encoded in the C_l's at large l. Since each l has associated with it $2l + 1$ components, we will have more information on the small scale anisotropies than on the large. In fact, upcoming experiments plan to measure each C_l with a fractional error of about $1/\sqrt{l}$ out to $l > 1000$.

This is an enormous amount of information, and we are only now beginning to realize the power of this information. Stated another way, we will have thousands of measurements, each with a signal to noise ratio of

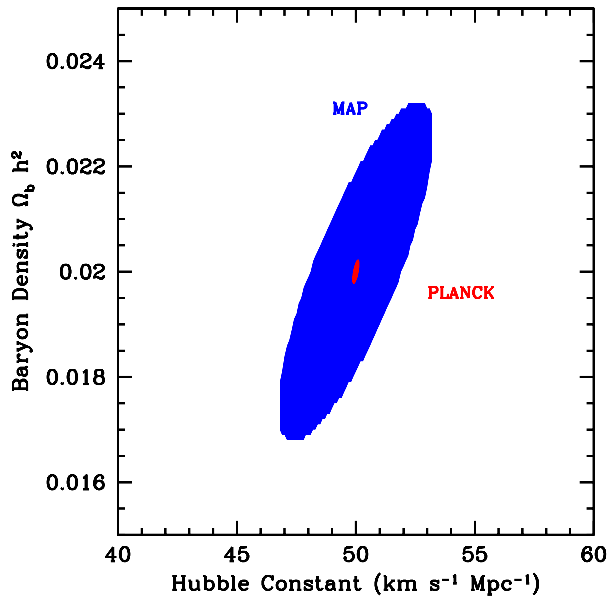

Figure 1. Allowed values of baryon density and Hubble constant after successful MAP and PLANCK missions.

better than ten to one. And we can compare these measurements to linear theory! We are truly living in the golden age of cosmology.

One way to understand the impact these observations will have on cosmology is to assume that inflation + Cold Dark Matter is the correct theory of structure formation. Such a theory has a number of free parameters: the amplitude and spectral index of the primordial perturbation; the Hubble constant; the baryon density; and the ratio of the tensor to scalar contribution to the anisotropies. If we pick a value in parameter space and generate a map of the CMB, we can analyze the map and find the error ellipses in the parameter space[3]. Since the parameter space is five dimensional, I will project out three of the dimensions and simply show the remaining ellipses in the two dimensional subspace (this corresponds to allowing the other three parameters to vary arbitrarily). The two-sigma allowed region in the (Baryon Density, Hubble constant) plane is shown in Figure 1. Needless to say, the results are spectacular: the error bars are much smaller than present errors, by a factor of ten or more.

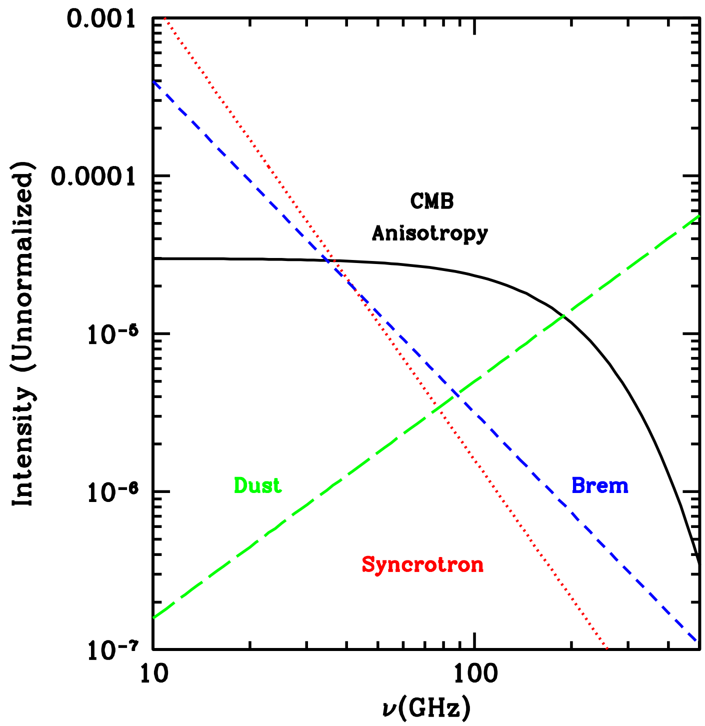

Figure 2. Spectrum of Foregrounds vs Frequency

3. Potential Spoilers

Since the pay-off is so large, we need to think hard about possible problems that might arise and spoil these accurate determinations. Let us consider three possibilities: foregrounds, reionization, and defect theories.

3.1. FOREGROUNDS

The signal in a CMB experiment will undoubtedly be contaminated by non-cosmic contributions. In particular our galaxy emits copious radiation in the microwave region. Figure 2 shows the spectra of several different components. There are two important points about this figure: First, the shapes of the spectra are sufficiently distinct that an experiment with good frequency coverage can trivially extract the cosmic black-body component. Indeed, upcoming experiments take measurements at many different frequencies. The second point has to do with the normalization of the spectra.

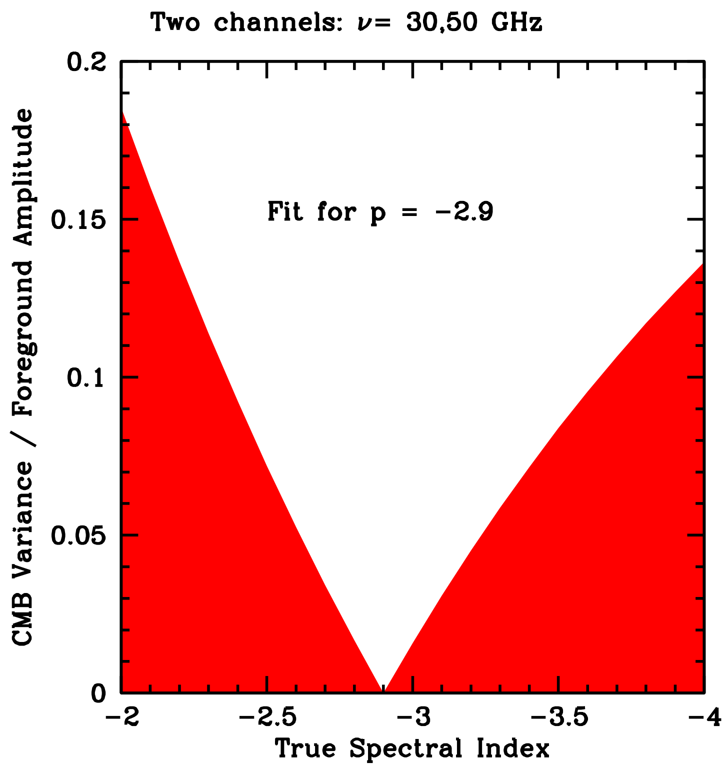

Figure 3. Extra Variance induced by uncertainty in the spectrum of foregrounds. One assumes a spectral index of -2.9; plotted is the variance as a function of the true spectral index. Even for large errors (index far from -2.9) the induced variance is a small fraction of the foreground amplitude.

I have not put in units, nor do I claim that the lines represent the RMS over the whole sky. But I do claim that the relative normalizations are roughly right. Specifically, there appears to be a fairly large region in frequency space $30 < \nu < 100$ GHz over which the cosmic signal is the dominant one. This situation is a bit of a surprise and arises because foregrounds are coming in slightly lower and the CMB is coming in slightly higher than anticipated.

The simplest technique for extracting the cosmic signal is to leave the amplitudes of the various components free, but assume a known spectral shape for each of them[4]. This is well justified in the case of the black-body and bremmstrahlung; in both cases theory restricts the spectrum. For syncrotron radiation and especially for dust, this is not so. The spectral index of syncrotron radiation varies from $-2.3 \rightarrow -3.1$ over the sky and the variation for dust is even worse.

One might worry, then, that extracting the cosmic signal from the foregrounds by fitting for amplitudes will lead to large errors if the assumed spectral index of the foregrounds differs greatly from the true index. Figure 3 shows that this is not true. In fact, even a relatively large error in the spectral index leads to only small errors in the CMB temperature determination[5]. More work needs to be done on the extraction process, but these – and other – preliminary studies[6] suggest that *foregrounds will not be an intractable problem.*

3.2. REIONIZATION

If the universe was reionized, the free electrons could have scattered with the photons, thereby washing out the primordial signal encoded in the C_l's. The degree to which the signal washes out depends on how early the universe was reionized. If reionization took place only recently, the electrons were so diffuse that they affect the photon spectrum hardly at all. On the other hand, if reionization took place at redshift greater than a hundred, virtually all of the signal would have been eliminated.

Fortunately, current observations indicate that reionization must have taken place relatively late. For, the signal at scales on the order of a degree is quite strong, much stronger than it would be if the universe was reionized early on. There is still the possibility of reionization at redshifts less than fifty or so. But this would just serve to modify the anisotropy spectrum [7],[8],[9] and could easily be incorporated into the analyses which will determine cosmological parameters.

3.3. DEFECT THEORIES

The error estimates shown in figure 1 assumed that the underlying physical theory was inflation + cold dark matter. What if this is wrong? If it is wrong in a small way, the error estimates are still valid. For example, if the true theory is inflation + cold + hot dark matter, the ellipses would change only slightly. Similarly, the parameters would still be well determined if there was a non-zero cosmological constant. We need to account for these possibilities but they will not undermine the program of parameter determination.

A more radical departure from (inflation + cold dark matter) will undermine the program. If structure formed because a network of topological defects were set up during an early phase transition, the resulting anisotropies are expected to be completely different. We cannot simply add another free parameter to our fitting algorithm. Until very recently, then, it was possible to argue that the discussion of parameter estimation was wishful thinking.

DEFECTS	INFLATION
• Classical	• Quantum
• Non–Gaussian	• Gaussian
•	•
•	•
•	•
• Vectors Important	• Tensors Important
• ISW	• No ISW
• Scalar Peak: Sine Mode	• Scalar Peaks: Cos Mode
• No Noticable Peak	• Noticable Peaks

Figure 4. Differences between Defect theories and Inflation.

If the true theory turned out to be cosmic strings, then none of the cosmological parameters would be determined by the CMB.

There has been a great deal of work on the anisotropies in defect theories[10]. We need to know what this viable alternative predicts and how this prediction compares with observations and with inflation. Recently, a group of us[11] undertook a large numerical investigation of this problem. We took the string simulation of Allen and Shellard[12], calculated the stress-energy tensor at all times and positions, fed these into a well-tested Boltzmann

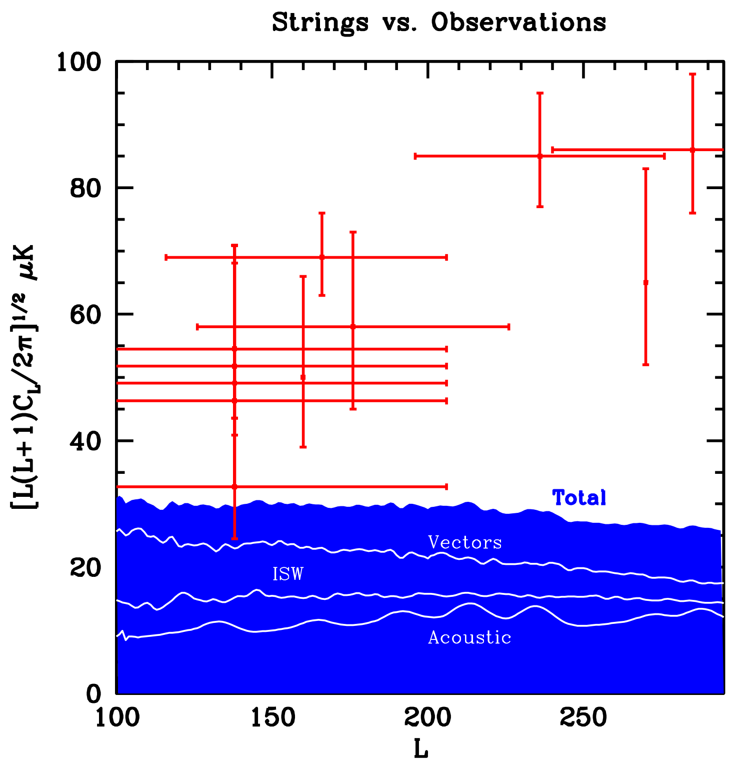

Figure 5. Anisotropy Spectrum for Local Cosmic Strings vs. Observations.

code, and calculated the C_l's. There are two features of our analysis that I wish to stress. First, we used all the components of the stress-energy tensor. Previous analyses assumed coherence so only looked at the equal time correlations or modelled the stress-energy tensor without using simulations directly. Second, we tested our results. This is important because the calculations are involved and there are many opportunities for error (believe me!). Our most convincing test involved simulating a single domain wall, and putting the resulting stress-energy tensor through the same pipeline as the string network. The key point is we know analytically the answer in the domain wall case, so we can check the code. The agreement is excellent.

I believe there are a number of results emerging from this work which supplement the (already lengthy) list of differences between defect theories and inflation. Figure 4 shows some of the standard differences together with our new conculsions. Foremost among these is that vector perturbations to the metric are important and we do not expect Doppler peaks.

Figure 5 shows our results compared with current observations. The

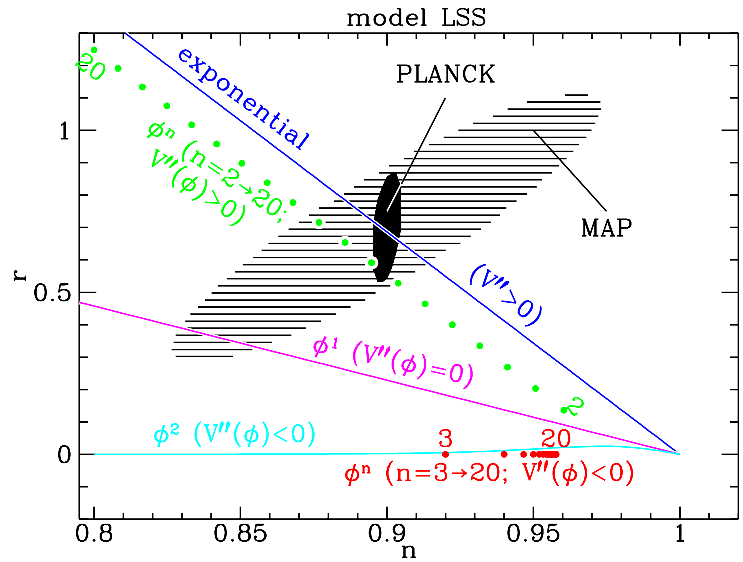

Figure 6. Allowed region in $n - r$ plane after succesful MAP/PLANCK missions. Dots and lines refer to predictions of various inflationary theories.

predictions[13] clearly disagree with the data. This discrepency, coupled with a similar discrepency in the matter power spectrum, has led many theorists to abandon defect theories as viable alternatives to inflation.

4. Conclusions

Upcoming experiments may well determine cosmological parameters to unprecedented accuracy. A number of recent developments suggest that we will succeed in this quest to measure parameters. First, foregrounds are coming in lower than anticipated. Second, the cosmic signal is coming in slightly higher than anticipated. This second development is crucial because it strongly suggests that reionization took place at very late redshift. Third, recent numerical calculations of defect theories suggest that inflation fits the current data far better than do defect theories.

I want to close by shifting focus somewhat. Until now, I have hammered away at the idea that we will be able to pin down cosmological parameters. Determining parameters is more than simply saying $H_0 = 61$ instead of $H_0 = 50$. Rather, some of the parameters will teach us deep things about physics. An example is shown in figure 6[14]. Here the error ellipses from satellite experiments are shown in the (Spectral Index, Tensor/Scalar Ratio) plane. The assumed "true" model has $(n = .9, r = .7)$, which by the way is not a bad fit to all current data[15]. These parameters are important because different inflationary models make different predictions in this plane. For example, an exponential potential leads to the prediction $r = 7(1-n)$. The predictions of many models are superimposed on the error ellipses in figure 6. It is clear that a large fraction of these models will be ruled out by the satellite missions. If we do indeed measure parameters to the accuracy expected, we can hope to learn a great deal about the very early universe.

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