MAP AND PLANCK VS THE REAL UNIVERSE

Douglas Scott
University of British Columbia

ABSTRACT.
The Microwave Anisotropy Probe (MAP) and Planck Surveyor satellites promise to provide accurate maps of the sky at a range of frequencies and angular scales, from which it will be possible to extract estimates for cosmological parameters. But the real Universe is a nasty, messy place, full of non-linear astrophysics. It is certainly clear that MAP and Planck will fix the background cosmology at an unprecedented level. However, they will have to contend with everything that the Universe throws at them: multiple foregrounds; structure formation effects; and other complications we haven’t even thought of yet. Some examples of such effects will be presented.

Only an ideal, theorist’s universe can be described by a number of free parameters in the single digits, while in reality it is likely that a greater wealth of information waits to be discovered. These ‘higher-order’ processes should be considered as potentially measurable signals, rather than contaminants. The capabilities of Planck seem ideally suited to fully understanding the physics encoded in the microwave sky.

1 Introduction

The MAP and Planck satellite missions clearly seem capable of returning large quantities of interesting cosmological data (some details of the missions are discussed by Charles Lawrence in these proceedings). What I’d like to focus on here is a consideration of some of the real things which MAP and Planck might be faced with. A couple of the examples that I will discuss make connection with recombination and with large-scale structure, both mentioned in the title of this meeting.

There should be no doubt that we will learn a great deal about the values of fundamental cosmological parameters from Cosmic Microwave Background (CMB) satellite missions. We have grown quite used to seeing tables of parameter uncertainties like the one below (Table 1, taken from the Planck Low Frequency Instrument – LFI – and High Frequency Instrument – HFI – proposals to ESA in February 1998, and adapted from Bond, Efstathiou & Tegmark 1997).

One thing to bear in mind is that making such a table is an intellectual exercise, rather than something you should necessarily put money on. First of all, the calculation depends on the specific input model. Secondly, it depends on the assumption that current models are all (or at least most) of the picture. Thirdly, it uses some simplifying assumptions about the residual effects of trying to extract foregrounds. And lastly, the experimental parameters may of course turn out to be quite different in practice. Nevertheless, construction of such tables is a valid way of comparing the potential of different experiments, and also can be a useful tool in deciding among experimental strategies.

Another related topic is that of parameter degeneracies (discussed in detail by Dan Eisenstein). There will always be combinations of parameters that are much better constrained than the fundamental parameters themselves (which is why \( \Omega h^2 \) appears in Table 1). For CMB anisotropies, this is particularly true of combinations that preserve ‘angular diameter distance’. Recently it seems to have become fashionable to suggest that this presents some sort of catastrophic problem for interpreting the results of CMB experiments. However, these degeneracies are easily lifted by using CMB data in association with other data sets. In any case, it would be foolish to view the CMB anisotropy data in isolation. Polarization information will also help break the degeneracies (see...
Douglas Scott

Table 1. Uncertainties in extracted cosmological parameters. The input model was standard CDM, with the usual fiducial parameter values, e.g. \( h_0 = 0.5 \). 65% of the sky was assumed to be foreground free, and polarization was not used. Here \( h \) is the usual dimensionless Hubble parameter, the \( \Omega_X \) are the density parameters in various components, \( n \) is the tilt of the initial conditions, \( T/S \) is the tensor (gravity wave) contribution and \( \tau \) is the optical depth since reionization.

| Parameter                        | MAP   | LFI   | HFI   |
|----------------------------------|-------|-------|-------|
| \( \delta h/h_0 \)              | 0.11  | 0.06  | 0.02  |
| \( \delta (\Omega_b h^2)/h_0^2 \) | 0.10  | 0.04  | 0.02  |
| \( \delta (\Omega_c h^2)/h_0^2 \) | 0.28  | 0.14  | 0.05  |
| \( \delta (\Omega_b h^2)/h_0^2 \) | 0.05  | 0.016 | 0.006 |
| \( \delta (\Omega_c h^2)/h_0^2 \) | 0.05  | 0.04  | 0.02  |
| \( \delta n \)                   | 0.04  | 0.01  | 0.006 |
| \( \delta (T/S) \)               | 0.24  | 0.13  | 0.09  |
| \( \delta \tau \)                | 0.19  | 0.18  | 0.16  |

The realism of this estimate could be improved by including effects from partial sky coverage, or noise enhancement introduced when removing foregrounds. But let us not dwell on such details here, keeping in mind that the experimentally determined values may be quite different in any case. The basic raw noise power spectra for MAP, LFI and HFI are shown by the solid lines in Figure 1. They cross the standard Cold Dark Matter power spectrum (to choose a specific example) at the places shown; for this specific calculation, the crossing points are \( \ell = 553, 1100 \) and 1738 for MAP, LFI and HFI, respectively.

Now the total number of spherical harmonic amplitudes (a.k.a. \( \alpha_{\ell m} \)’s) up to some maximum value of \( \ell \) is

\[
\sum_{\ell=2}^{\ell_{\text{max}}} \sum_{m=-\ell}^{+\ell} = \ell_{\text{max}}(\ell_{\text{max}} + 2) - 3.
\]

So the number of modes up to \( \ell_{\text{max}} \) is roughly \( \ell_{\text{max}}^2 \). This estimate can be used to give a measure of the number of modes with signal-to-noise greater than unity, or the information content of the maps that will be produced. For MAP, LFI and HFI, us-

1 In more detail, many modes will be measured with much higher signal-to-noise, and in addition it will be possible to obtain binned information on the power spectrum.
Figure 1. Estimated noise power spectra for MAP and the LFI and HFI parts of Planck (solid lines). These are calculated using recent estimates for the noise performance and beam-size at the various frequencies. The noise spectra are essentially \( C_\ell = \text{constant} \) up to the beam-size, after which they increase exponentially. Although these are only estimates of how well the experiments might do, the cosmological power spectrum is, of course, much less well known! The standard Cold Dark Matter, and an open CDM model (as an example of a model with much more small-scale power) are illustrated.

Even where the noise dominates, we also haven’t worried about what we mean exactly by signal-to-noise, and whether this is per \( C_\ell \) rather than per \( a_{\ell m} \), i.e. we ignored cosmic variance.

### 2 Foregrounds

The obvious complication for satellite measurements of the background lies in extracting any foreground signals that might contaminate the signal. There are many and varied possible foregrounds, but I restrict myself to some general points here. At a crude level, all the current evidence suggests that foregrounds will not be very important. However, at a detailed level, it is obviously important to extract them in order to squeeze out the maximum cosmological information.

The only real way to estimate the effect of relevant foregrounds is to measure them. And the only confident way of removing them from CMB maps is to fully characterise them in the data set. There are three ways to get at the foreground signals:

- (i) spatial information, including correlation with the structure of the Galaxy and known sources, as well as auto-correlation information (i.e. different power spectra than the primordial signal);
- (ii) different variation with frequency than the thermal CMB fluctuations; and
- (iii) statistics which are probably far from Gaus-
sian.

To use these methods to dig out the foregrounds will require the highest achievable sensitivity, full sky coverage and the widest possible range of frequencies. These are the design drivers for both the MAP and Planck missions. MAP has every chance of being able to characterise the important low frequency foregrounds at moderate angular scales. Planck will be able to do this for high frequencies as well, and at greater angular resolution and sensitivity.

3 Other Effects

There are a great many possible effects that could change the CMB anisotropies compared with the current best calculations (as discussed by Naoshi Sugiyama at this conference). Some have already been described by Hu et al. (1995) and in a large number of other papers (see also Mark Kamionkowski’s contribution). At the level of basic physics, there are still some potential surprises out there (see the next section, as a case in point), and many examples exist of effects that do change the anisotropies if not included properly, e.g. polarization, helium abundance, precise CMB temperature, precise physical constants, etc. In addition, there are similar things that have already been examined and which are probably not important, such as relativistic effects, and scattering other than Compton/Thomson scattering at low redshift (e.g. Rayleigh and molecular resonant scattering), and at high redshift (e.g. double Compton and the like).

On the particle physics side, there are issues like extra relativistic degrees of freedom, decaying particles, neutrino decoupling, massive neutrinos, (not quite weakly) interacting particles, warm dark matter, primordial magnetic fields, non-zero chemical potentials, non-trivial initial conditions (running spectral indices, etc.), alternative theories of gravity, topological defects, dynamical fields, and probably a great many other things besides. Which of these might live in the same universe as us is a matter of personal opinion!

Certainly the Real Universe contains smallish scale objects at low redshifts, and this fact gives rise to a great many astrophysical effects. Some examples are reionization (including ‘patchy’ reionization, and quasar bubbles), thermal and kinetic Sunyaev-Zel’dovich effects, the Rees-Sciama effect from non-linearly evolving potentials, gravitational lensing, higher order lensing and potential effects, the Ostriker-Vishniac lensing, possible mixed spectral-anisotropy scattering effects, etc. Many of these examples lead to processing of the primordial CMB signal, particularly at small angular scales, leading to potentially measurable consequences. A great deal of work has been done investigating some of these processes, but almost no work on others. The above lists should serve as an indication that potentially there are several more things that haven’t even been imagined yet. The two following examples illustrate areas that I have been directly involved in studying, and where there were indeed some surprises.

4 Recombination

Figure 2 shows the cosmic recombination calculation of Seager, Sasselov & Scott (in preparation). We revisited the calculation (which has changed little since the 1960’s), trying to make as few approximations as possible. This led us to consider models of hydrogen atoms containing up to 300 levels, and in addition detailed modelling of helium, collisional processes, molecular chemistry, and many more nitty-gritty details than we ever thought possible. The goal was to make sure we could follow the recombination history of the Universe accurately enough for calculations of CMB anisotropies at the 1% level.

We found several minor improvements to the traditional recombination calculations, as well as at least two important ones. Firstly, careful treatment of helium results in the somewhat surprising conclusion that He II recombines only just before hydrogen does (with almost no change for He III recombination). Our new calculation is shown by the solid line in Figure 2, while the old calculation,
Figure 2. New calculation of recombination with the parameters of the standard Cold Dark Matter model. Here \( x_e \) is defined as the ratio of free electrons to hydrogen atoms, and so the steps at higher redshifts are the two recombinations of helium.

equivalent to Saha equilibrium, is the dashed line.

The second thing is that, at low redshifts, the upper levels in the hydrogen atom are not in equilibrium, and are actually over-populated. This leads to a lower ionization fraction at low \( z \)'s than in the standard calculation. From about \( z \sim 800 \), we see a lowering of \( x_e \) by around 10\% of its value (this is cosmology-dependent). This difference is buried around \( x_e = 0 \) in the figure, but represents a non-trivial difference in the optical depth back to these redshifts.

Figure 3 shows the effect of our new calculation on the CMB power spectrum. The two main effects conspire to have the same overall sign, and both increase the anisotropies a little, with an increasing relative amount at small angular scales. The figure is explicitly for standard CDM, and although the results vary with cosmology, the same general trend is seen. The y-axis on the plot is the fractional change in the \( C_\ell \)'s, normalized to have the same initial condition amplitude, or equivalently the same matter power spectrum. The change is even bigger than 5\% at the highest \( \ell \)'s plotted here – but of course the amplitude of the power spectrum is actually quite low at such small scales.

The physics behind the changes is quite simple to understand. Firstly the change in \( x_e \) at low redshifts leads to less suppression of the anisotropies from the amount of scattering in the low \( z \) tail of the visibility function. The change in optical depth out to, say, \( z = 800 \) is around a per cent or two. This leads to less suppression of the anisotropies at almost all multipoles (above \( \ell \)'s of several tens) by about twice this amount, which is what we find. This partial erasing of the anisotropies is the sort of detailed effect that doesn’t get discussed too much, even if the experts have always been doing it right. Now it would appear that you have to be more careful about what \( x_e(z) \) you put in. We have also found that it is possible to obtain roughly the correct answer with simpler methods than running code with 300 level hydrogen atoms.

The second effect is that the change in the helium recombination results in more scattering at high redshifts, which, in turn, leads to a change in the sound horizon scale. The phases of the acoustic oscillations depend on an integral over the sound speed, which is different now that we think there are more free electrons at \( z \sim 1500-2000 \). The change in the \( C_\ell \)'s is basically what you would get by assuming the wrong sound horizon. Again, we find that it is quite straightforward, in hindsight, to adapt the old calculation to deal properly with helium.
5 Sub-mm Point Sources

SCUBA (the Sub-millimeter Common-User Bolometer Array) is a sensitive camera now routinely detecting cosmological sources at the James Clerk Maxwell Telescope (Holland et al. 1998). In a sense, it is the ‘Cosmic Dust Pan’, since a combination of the properties of the sky and the galaxies themselves makes the SCUBA 850 µm filter ideal for studying distant dusty galaxies. This waveband corresponds closely with the 353 GHz channel planned for Planck. Several groups have now obtained estimates of 850 µm source counts at around a few mJy, and it is fair to say that there are many more sources than originally anticipated. An immediate question raised by these SCUBA observations concerns the implications for Planck.

Figure 4 shows a summary of the source count observations (see Scott & White 1998 for references). The solid line is a two power law phenomenological model that passes through the counts and also fits the observed sub-mm background. The horizontal line shows the equivalent number of pixels (assuming there to be 10 per FWHM at this frequency) for Planck. Fluctuations in the numbers of these sources look like they might be detectable by Planck.

In more detail, we can take the model for the counts and calculate the contribution to CMB anisotropies:

\[ C_\ell(\nu) = \int_0^{S_{\text{cut}}} S_\nu^2 \frac{dN}{dS_\nu} dS_\nu + w_\ell \left( I_{\nu,FIB} \right)^2, \]

assuming that all sources with \( S > S_{\text{cut}} \) are removed. Here, \( I_{\nu,FIB} = \int S (dN/dS) dS \) is the background contributed by sources below \( S_{\text{cut}} \). The first term is the Poisson ‘shot-noise’ term, and is plotted by the curve labelled ‘Poisson’ in Figure 5. In the second term, \( w_\ell \) is the Legendre transform of \( w(\theta) \), the two-point correlation function of the sources. Essentially nothing is known about the clustering properties of the SCUBA galaxies. However, if we assume that they are clustered as strongly as Lyman break galaxies at \( z \sim 3 \), and that this extends out to \( \ell \sim 100 \), then we obtain the curve labelled ‘Clustered’ in the figure.

This Poisson calculation made quite conservative assumptions based on the present data. There seems little doubt that Planck will be able to detect this signal as excess white noise. The clustering signal plotted in Figure 5 may be...
somewhat optimistic, but it serves as an example of how strong such a signal might be. At lower frequencies, for example the 220 GHz channel, the contribution of these sources to the anisotropy is greatly diminished, and they are expected to be entirely negligible at still lower frequencies.

The bottom-line is that the sub-mm sources revealed by SCUBA will not have a strong impact on the most important goal of the Planck mission, that of precisely characterising the CMB anisotropy. For the entire Low Frequency Instrument, and the three lowest frequency channels of the HFI, there will be no significant contribution from these distant galaxies. Certainly, the signals in the higher frequency channels can be used to remove point sources and recover most of the CMB information even at 353 GHz. Moreover, the possibility of actually measuring the Poisson and clustering signals over most of the sky for these galaxies provides Planck with yet another way of tackling fundamental cosmological issues.

6 Conclusions

We now know a great deal from the already detected CMB anisotropies (see Lawrence, Scott & White 1998 for a discussion that grew out of this meeting). Certainly, we will learn a great deal more from future ground- and balloon-based experiments. But the promise of the satellite missions, MAP and Planck, is nothing short of astonishing. Undoubtedly, we will find out a lot about the Universe from the data these satellites return. However, it is important to remember that they will be measuring the real sky, rather than some theorist’s ideal one. This means that, on the one hand, there may be some complications lying ahead of us, but on the other hand, there may be much more exciting science to be mined from these datasets than are currently in our models.

Acknowledgments

Parts of this paper are based on work carried out in collaboration with Dimitar Sasselov, Sara Seager and Martin White. I would also like to thank members of the LFI consortium for useful discussions. This research was supported by the Natural Sciences and Engineering Research Council of Canada.

References

Bond, J.R., Efstathiou, G., Tegmark, M., 1997, MNRAS, 291, L33
Holland, W.S., et al., 1998, MNRAS, in press
Hu, W., Scott, D., Sugiyama, N. & White, M., 1995, PRD, 52, 5498
Lawrence, C.R., Scott, D. & White, M., 1998, Comm. Astrophys., submitted
Scott, D. & White, M., 1998, A&A, submitted; preprint astro-ph/9808003