ΛCDM and the WMAP power spectrum beam profile sensitivity

Utane Sawangwit & Tom Shanks
Department of Physics, Durham University, South Road, Durham DH1 3LE, England

We first discuss the sensitivity of the WMAP CMB power spectrum to systematic errors by calculating the raw CMB power spectrum from WMAP data. We find that the power spectrum is surprisingly sensitive to the WMAP radiometer beam profile even at the position of the first acoustic peak on ≈ 1 degree scales. Although the WMAP beam profile core is only 12.6 FWHM at W, there is a long power-law tail to the beam due to side-lobes and this causes significant effects even at the first peak position. We then test the form of the beam-profile used by the WMAP team which is based on observations of Jupiter. We stacked radio source beam profiles as observed in each WMAP band and found that they showed a wider profile in Q, V, W than the Jupiter profile. We have now checked that this is not due to any Eddington or other bias in our sample by showing that the same results are obtained when radio sources are selected at 1.4GHz and that our methods retrieve the Jupiter beam when it is employed in simulations. Finally, we show that the uncertainty in the WMAP beam profile allows the position as well as the amplitude of the first peak to be changed and how this could allow simpler cosmologies than standard ΛCDM to fit the CMB data.

1 Introduction

The standard ΛCDM cosmological model is a quite perplexing mixture of impressive observational successes (e.g. Hinshaw et al.1, Komatsu et al.2, Hicken et al.3, Kessler et al.4) coupled with wider implications which make the model complicated to the point of implausibility (e.g. Weinberg5). Some fundamental and astrophysical issues for the standard model are as follows:

- The exotic, weakly interacting, particles envisaged as candidates for the dark matter component of the standard model are still undetected in the laboratory (e.g Aprile et al.6).

- The inclusion of a cosmological constant means that ratio of the vacuum energy density to the radiation energy density after inflation is 1 part in 10^{100}, a fine-tuning coincidence which leads to appeals to the anthropic principle for an explanation (e.g Efstathiou7).

- Even if fine-tuning arguments are regarded as unsatisfactory, the problem is that inflation was set up to get rid of fine-tuning in terms of the ‘flatness’ problem (Guth8) and so the introduction of more fine-tuning with the cosmological constant appears circular.

- Λ has the wrong sign for string theorists who prefer a negative Λ than a positive Λ, ie a cosmology which is approximately Anti-de Sitter rather than de Sitter (e.g Witten9).

- The standard inflationary model predicts not just one but 10^{1077} Universes (Steinhardt10).
Multipole moment \((l)\)

\[
l(l+1)C_l / \frac{l}{2 \pi} \left( \mu K^2 \right)\]

WMAP5 (Nolta et al. 2009)

W1W2 (KQ85)

Figure 1: The red line shows the raw WMAP W band power spectrum estimated from the cross-correlation of the WMAP5 W1 and W2 maps. The blue diamonds + line shows the final WMAP5 spectrum after ‘de-beaming’ using the Jupiter beam (+’cut-sky’ correction). The large effect of de-beaming even at the first acoustic peak \((\approx 1\text{deg})\) is caused by beam sidelobes, even though the beam’s Gaussian core has a width of only 12.6 FWHM.

- Astrophysically, any CDM model in the first instance predicts a featureless mass function for galaxies whereas the galaxy luminosity function shows a sharp ‘knee’ feature (eg Benson et al.\(^{11}\)).

- CDM models predict that large structures should form last and therefore should be young whereas, observationally, the largest galaxies and clusters appear old (eg Cowie et al.\(^{12}\)).

- To fix the above two problems, large amounts of feedback (eg Bower et al.\(^{13}\)) are invoked which results in more energy now being used to prevent stars forming than in forming them under gravity.

2 WMAP CMB Power Spectrum

The above issues mean that the standard model requires remarkable observations in its support and the most remarkable of these is represented by the acoustic peaks in the CMB power-spectrum as measured by WMAP (eg Hinshaw et al.\(^{14}\)) and other CMB experiments. Much therefore depends on the accuracy of these observations and in particular on the position of the first acoustic peak at wavenumber \(l=220\) or \(\approx 1\text{deg}\). A first peak at scales as large as these strongly favours a CDM model. Attempts have been made to move the first peak using cosmic foregrounds such as large clusters via the SZ effect (Myers et al.\(^{15}\), Bielby et al.\(^{16}\)) or gravitational lensing (Shanks\(^{17}\)) or even inhomogeneous reionisation at \(z \approx 10\) but generally the effects have been small.

At first sight, it seems unlikely that any observational effect of the resolution of CMB radiometers such as those used by WMAP on the position and amplitude of the first peak could be significant. The highest resolution of the WMAP satellite comes at the 94GHz W band where the core of the beam profile has 12.6 FWHM (eg Page et al.\(^{18}\)) and it seems unlikely that such a narrow beam profile would have an effect at the \(\approx 1\) degree scale of the first peak. However, Sawangwit and Shanks\(^{19}\) have recalculated the WMAP5 power spectrum, \(C_l\), by cross-correlating the maps from the W1 and W2 detectors as an example. This raw spectrum is compared in Fig. 1 to the WMAP5 spectrum that is usually fitted by the standard model and large differences can be seen even at the scale of the first acoustic peak, where the raw spectrum is a factor of \(\approx 2\) lower than expected. Most of the reason for this difference (\(\approx 70\%\)) is the effect
of the WMAP beam profile with the remainder being due to sky incompleteness. Although the W band beam profile has its narrow, 12.6', core, it also has wide sidelobes which fall off as a power-law with angle, rather than as a Gaussian. The WMAP beam profile is usually estimated by measuring bright planetary sources such as Jupiter and the beam must be known to high accuracy at 1 degree scales where the profile reaches 0.1% of its peak value. Thus the effects of 'de-beaming' are ≈ 70% of the first peak height and even more at the position of the second and third peaks.

3 Testing the WMAP beam using radio sources

The sensitivity of the WMAP power spectrum to the beam profile suggests that it is important to test the profile used by the WMAP team. Sawangwit and Shanks [19] stacked the CMB data at the positions of ≈ 150 – 250 WMAP5 radio sources as catalogued by Wright et al. [20], excluding all sources identified as extended in ground-based, higher resolution 5GHz surveys (see Fig. 2). They found that at the Q, V and W bands, the stacked source profiles looked increasingly broad and broader than the Jupiter profile on scales of 10 – 30'. Beyond these scales, the noise on the stacked radio-source profile means that little information about the profile can be obtained by this method. Sawangwit & Shanks [19] also found more marginal evidence that the profile width may increase as source flux decreases, possibly suggesting that there was a non-linearity in the WMAP flux scale.

In Fig. 2 we also show a new WMAP stack on the positions of a flux limited selection of NVSS sources at the 1.4GHz frequency, now rejecting any source with a neighbour within a 1 degree radius. As can be seen, we find an almost exactly similar result to that based on selecting sources from the WMAP5 catalogue. We have further found that the result reproduces in the sample of sources detected using the ‘CMB-free’ method of Chen and Wright [21]. Sawangwit [22] has also checked our result in 100 CMB sky simulations, each containing a similar number of sources as in the WMAP5 source list and with each source assuming the Jupiter beam profile. We found that in this simulated case our stacked radio source profile retrieved the Jupiter beam almost perfectly. All of these tests suggest that our results are not subject to any ‘Eddington bias’ or any other bias.
4 Other models that fit the WMAP CMB Power Spectra

Sawangwit and Shanks\cite{19} fitted power-laws to the WMAP radio source beam profile (see Fig. 2) and showed how sensitive the height of the first acoustic peak is to relatively small deviations away from the Jupiter profile. Here we show that beam profiles that are consistent with the radio sources can also significantly shift the position of the first peak from the standard $l = 220$ multipole to $l > 300$. We do this by reverse engineering a beam profile, $b_s(\theta)$, from the square of the beam window function, $b_l$, obtained by dividing the $C_l$ of a model with $\Omega_{\text{baryon}} = 1$, $H_0 = 35\text{ km s}^{-1}\text{Mpc}^{-1}$ and $\tau = 0.35$ (Shanks\cite{24,25,26}) by the ‘raw’, W1W2 $C_l$ shown in Fig. 1. Transforming back to the beam profile, $b_s(\theta)$, leaves a profile which shows a ‘ringing’ at large $\theta$ and which oscillates between positive and negative values. After only taking the small-scale part of the profile which is positive and ‘squeezing’ the profile to smaller scales by 25% to compensate for the loss of the negative parts gives us a ‘do-it-yourself’ profile for the large scales. At $\theta < 20'$ we fit the radio source profile with a Gaussian and then an exponential which helps match the Gaussian smoothly onto the large scale part. The resulting profile is shown in Fig. 3, where it is compared to the WMAP and NVSS radio source W band profile and the Jupiter profile. It is the spike at $\approx 35'$ which is vital to move the $l = 220$ peak to match the $\Omega_{\text{baryon}} = 1$, $C_l$ peak at $l = 330$. The resulting ‘do-it-yourself’ W band $C_l$ compares well to the theoretical $\Omega_{\text{baryon}} = 1$, low $H_0$ $C_l$ on which it is based (see Fig. 4); the raw W1W2 $C_l$ is also shown. Beyond $l = 600$ where the S/N for the WMAP spectrum drops, the $C_l$ from the QUAD experiment (Brown et al.\cite{23}) is also plotted. Again, we see broad agreement with the $\Omega_{\text{baryon}} = 1$ model, although there is some detailed disagreement with QUAD peak positions at $l > 1000$.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3.png}
\caption{A partly ‘reverse-engineered’ or ‘do-it-yourself’ WMAP W band beam profile comprising a Gaussian in the centre (solid black line), then an exponential (dashed black line) and then a spike (dot-dashed black line). This beam is not inconsistent with the radio source profiles and produces the $C_l$ given by the red solid line in Fig. 4.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4.png}
\caption{The $C_l$ debeamed using the ‘do-it-yourself’ beam from Fig. 3 is shown as the red line and the $\Omega_{\text{baryon}} = 1$, low $H_0$ model and the raw WMAP5 W1W2 $C_l$ from which it was partly reverse engineered are shown as the solid black and blue lines. This model is also compared to the QUAD results at $l > 600$ (red open circles).}
\end{figure}

5 Conclusions

We have discussed various fundamental and astrophysical problems for the standard $\Lambda$CDM cosmological model, including its requirement for undiscovered physics in terms of the weakly interacting CDM particle and in the one part in $10^{100}$ fine-tuning in terms of the small size of the cosmological constant. But the model has received overwhelming support from CMB
experiments such as WMAP in terms of the position of the first acoustic peak in the power spectrum. However, Sawangwit and Shank[19] have shown the high sensitivity of the amplitude of the first acoustic peak to the detailed form of the WMAP instrumental beam profile and that stacking unresolved radio sources indicates wider beams than expected in the Q, V and W bands. Here we have shown that a WMAP W band beam which is not in consistent with the radio source beam profile can also reproduce the power spectrum of a simple inflationary model with $\Omega_{\text{baryon}} = 1$ and a low value of $H_0$. This model produces a peak at multipole $l = 330$ rather than $l = 220$. It also reproduces the broad form, although not the detailed peak positions, of the observed power spectrum in the $600 < l < 2000$ region from e.g the QUAD experiment. However, the $l = 330$ WMAP peak was basically ‘reverse-engineered’ to fit the $\Omega_{\text{baryon}} = 1$ model, using the freedom afforded by the loose constraints on the stacked radio source profiles at scales $\theta > 30''$ and it remains to be seen whether the actual WMAP beam is consistent with this very simple cosmological model.

Acknowledgments

We acknowledge the WMAP team for making their data freely and publicly available. Utane Sawangwit acknowledges a Royal Thai Government Scholarship for PhD funding.

References

1. G. Hinshaw et al, ApJS 148, 135 (2003).
2. E. Komatsu et al, ApJS submitted, arXiv:1001.4538 (2010).
3. M. Hicken et al, ApJS 700, 1097 (2009).
4. R. Kessler et al, ApJS 185, 32 (2009).
5. S. Weinberg, Rev. Mod. Phys 61, 1 (1989).
6. E. Aprile et al, Phys. Rev. Lett. submitted, arXiv:1005.0380 (2010).
7. G.P. Efstathiou, MNRAS 274, L73 (1995).
8. A.H. Guth, Phys. Rev. D 23, 347 (1981).
9. E. Witten, http://theory.tifr.res.in/strings/Proceedings/witten/22.html (2001).
10. P.J. Steinhardt, in The Very Early Universe, eds: Gibbons, GW, Hawking, SW and Siklos, STC (Cambridge: Cambridge University Press, 1983).
11. A.J. Benson et al, AJ 599, 38 (2003).
12. L.L. Cowie, A. Songaila and E. Hu, AJ 112, 839 (1996).
13. R.G. Bower et al, MNRAS 370, 645 (2006).
14. G. Hinshaw et al, ApJS 180, 225 (2009).
15. A.D. Myers et al, MNRAS 347, L67 (2004).
16. R.M. Bielby and T. Shanks, MNRAS 382, 1196 (2007).
17. T. Shanks, MNRAS 376, 173 (2007).
18. L. Page et al, ApJS 148, 39 (2009).
19. U. Sawangwit and T. Shanks, MNRAS accepted, arXiv:0912.0524 (2010).
20. E.L. Wright et al, ApJS 180, 283 (2009).
21. X. Chen and E.L. Wright, ApJ 694, 222 (2009).
22. U. Sawangwit, PhD thesis, Durham Univ., in prep. (2010).
23. M.L. Brown, ApJ 705, 978 (2009).
24. T. Shanks, Vistas in Astronomy, 28, 595 (1985).
25. T. Shanks et al in Observational Tests of Cosmological Inflation, Eds. T Shanks, AJ Banday, RS Ellis, CS Frenk and AW Wolfendale, (Kluwer, Dordrecht, 1991).
26. T. Shanks in Maps of the Cosmos, Eds. MM Colless, L Staveley-Smith and R Stathakis (ASP, San Francisco, 2005).