Dark Energy and the Cosmic Microwave Background

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Dark Energy and Simulations
Ringberg June 28, 2012
1. Introduction

2. Dark Energy and the CMB at the last scattering surface

3. Dark Energy and the CMB at low redshift
   - ISW
   - CMB lensing

4. Conclusions
Introduction

The CMB data

WMAP 7 year CMB sky

The WMAP Team
The CMB data is **precise** and **well understood**.

Most of it can be calculated within **linear perturbation theory** to percent accuracy.

The resulting anisotropy and polarization spectra depend on **a few cosmological parameters** and **a few parameters describing the initial conditions of the fluctuations**. Which can also be determined accurately.

### Minimal ΛCDM parameters (WMAP 7yr + ACT from Dunkley et al. ’11)

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- **Amplitude**: \( \Delta^2_R, n_s, \omega_m \).
- **Relative amplitude of even and odd peaks**: \( \omega_b \).
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Dark energy enters here only over \( D_A(z_*) \)!

\[
D_A(z_*) = \frac{1}{1 + z_*} \int_0^{z_*} \frac{dz}{H(z)} = \frac{h}{H_0(1 + z_*)} \int_0^{z_*} \frac{dz}{\sqrt{\omega_r(1 + z)^4 + \omega_m(1 + z)^3 + \omega_k(1 + z)^2 + \omega_{de}(z)}}
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Distance scaling of CMB spectra

\[ C(\theta) \equiv \langle \Delta T(n_1) \Delta T(n_2) \rangle = \frac{1}{4\pi} \sum_{\ell} (2\ell + 1) C_\ell P_\ell(\cos \theta) \]

\[ = \frac{1}{4\pi} \sum_{\ell} (2\ell + 1) C'_\ell P_\ell(\cos \theta') = C'(\theta') \]

For \( \ell \gtrsim 20 \)

\[ C_\ell = \left( \frac{D'_A}{D_A} \right)^2 C'_{\ell} \frac{D'_A}{D_A} \ell . \]
In Vonlanthen, Räsänen & RD ’10 we have studied how well we can fit the CMB with a cosmological model which is Einstein de Sitter up to last scattering and the distance to last scattering is arbitrary, $D_A = S D_{A,EdS}$.

Features on the lss are then simply seen under a different angle,

$$C_\ell = S^{-2} C_{S-1,\ell}^{EdS}.$$ 

With this we can fit all present CMB data with $\ell \gtrsim 40$.

⇒ CMB data with $\ell > 40$ measures very precisely $\omega_b, \omega_m, n_s$ and $D_A(z_*)$ or $S$, but it cannot determine the nature of dark energy.
Scaled spectra from curved cosmologies

Figure 5: The TT spectra for models with $\Omega_\Lambda = 0$, $\Omega_K \neq 0$. The solid curve corresponds to the Einstein-de Sitter universe, the dotted curve corresponds to a model with $\Omega_K$ as specified in the panels, and the dashed curve shows the Einstein-de Sitter universe power spectrum scaled with $S$. The vertical axis is $\ell(\ell+1)C_{TT}/(2\pi)$ in $(\mu K)^2$.

(from Vonlanthen, Räsänen & RD ’10)
Scaled spectra from curved cosmologies

Figure 6: As in figure 5, but for the TE spectra. The dotted curves are invisible since they are completely overlaid by the dashed ones (scaled model).

(from Vonlanthen, Räsänen & RD '10)
Scaled spectra from curved cosmologies

(From Vonlanthen, Räsänen & RD ’10)

\[ \Omega_K = 0.6 \]

\[ \Omega_K = -0.6 \]

\[ \Omega_K = 0.3 \]

\[ \Omega_K = -0.3 \]
Scaled spectra from $\Lambda$ cosmologies

Figure 8: As in figure 5, but for $\Omega_\Lambda \neq 0$, $\Omega_K = 0$. We consider two different values for $\Omega_\Lambda$, corresponding to the two columns. The rows from top to bottom mark the $T T$, $E E$ and $T E$ spectra.

B. Reionization

In this appendix we study the effect of reionization on the angular power spectrum of the CMB. If the baryons are reionized at redshift $z_{ri}$, then the effect on scales which are of the order of the horizon size at the time is complicated, and lead to additional polarization and a scale-dependent reduction of the amplitude of anisotropies. However, on scales which are well inside the horizon, the rescattering of photons simply reduces the amplitude of CMB temperature and polarization anisotropies by roughly the same amount on all scales. This effect can therefore be absorbed in a renormalization of the spectrum. In figure 9 we show the $T T$ spectrum with and without reionization for the best-fit $\Lambda$CDM model, as well as the relative difference of the spectrum with and without reionization. For $\ell \geq 40$, renormalizing the spectrum with a constant reproduces the effect of reionization within about 1.5%. We have done the same with the temperature–polarization cross-correlation and the polarization spectra. Also there renormalization is a very good approximation (better than 0.5% on average) for $\ell \geq 40$, see figures 10 and 11. To obtain the spectra with $\tau = 0 .1$, we have multiplied the spectra with $\tau = 0$ by factor 0.82.

(from Vonlanthen, Räsänen & RD ’10)
Figure 9: The TT power spectrum with (dashed, red) and without (solid, black) reionization for optical depth $\tau = 0$ for $\ell \geq 2$ (left upper panel) and $\ell \geq 40$ (right upper panel). For the upper panels, the vertical axis is $\ell(\ell + 1)C_{\text{TT}}/(2\pi)$ in ($\mu$K). In the lower panel we show the relative difference between the spectrum with and without reionization, when the latter is simply rescaled by a constant. For low $\ell$'s, the differences are substantial, up to 25%, but for the values $\ell \geq 40$ we consider, the difference is less than 2%.

(from Vonlanthen, Räsänen & RD '10)
Reionization

Figure 10: The TE correlation spectrum with (dashed, red) and without (solid, black) reionization for optical depth $\tau = 0$ for $\ell \geq 2$ (left upper panel) and $\ell \geq 40$ (right upper panel). The vertical axis is $\ell (\ell + 1) C_{\ell}^{TT} / (2 \pi)^2$ in ($\mu$K)$^2$. In the lower panel we show the difference between the spectrum with and without reionization, when the latter is simply rescaled by a constant. For the values $\ell \geq 40$ we consider, the difference is below 0.1($\mu$K)$^2$.

(from Vonlanthen, Räsänen & RD ’10)
Reionization

\[ \ell \geq 2 \quad \ell \geq 40 \]

(from Vonlanthen, Räsänen & RD '10)
Cosmological parameters

(from Vonlanthen, Räsänen & RD ’10)
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(from Vonlanthen, Räsänen & RD ’10)
CMB from $\ell \geq l_{\text{min}}$

Figure 2: The increase in the large-scale power with increasing $l_{\text{min}}$ in the best-fit $\Lambda$CDM models with $\tau = 0$. The lowest line corresponds to $l_{\text{min}} = 2$; the subsequent lines have $l_{\text{min}} = 40$, 60, 80, and 100, respectively. At $l_{\text{min}} = 120$ the large-scale power no longer increases but it decreases somewhat. The WMAP and ACBAR data are superimposed.

The vertical axis is $\ell(\ell + 1)C_{\ell} / (2\pi)^2$ in ($\mu$K)$^2$, which is usually attributed to reionization is now achieved with a somewhat redder spectrum. In order not to decrease the height of the acoustic peaks, this leads to a higher value of $\omega_c$. A redder spectrum also enhances the amplitude difference between the well-measured first and second peaks. This can be compensated by a reduction of $\omega_b$, since a larger $\omega_b$ means a larger difference between the odd contraction and even expansion peaks [26].

However, we have found that reionization is not the dominant effect, the systematic shift is also present if reionization is included in the analysis. We have checked this by including $\tau$ as a model parameter. The results of table 1 remain valid for also in this case. The problem is that for $l_{\text{min}} \geq 40$ the value of $\tau$ is degenerate with a normalization of the amplitudes (see discussion in Appendix B) and the best fit value for $\tau$ fluctuates significantly from chain to chain. We therefore prefer to show the results for $\tau = 0$. Note that the change is larger than the error bars. The shape of the one-dimensional probability distribution for the parameters is not for the most part significantly distorted, and the two-dimensional distributions do not show strong changes in the correlation properties as $l_{\text{min}}$ increases. Therefore, the error bars do accurately represent the statistical error estimate.

We conclude that the high $l$ data prefer different parameter values than the data

(from Vonlanthen, Räsänen & RD '10)
The integrated Sachs Wolfe effect (ISW)

On the way into our telescope CMB photons loose/gain energy if they move through a time-dependent gravitational potential:

\[
\left( \frac{\Delta T}{T} \right)_{ISW} (n) = \int_{t_0}^{t_\star} \partial_t (\Phi + \Psi)(t, x(t)) dt
\]

In a flat pure matter Universe \( \partial_t \Psi = \partial_t \Phi = 0 \). When \( \Lambda \) takes over, the gravitational potentials decay.
ISW from correlation with LSS

Correlation of the WISE (wide field infrared survey explorer) with WMAP 7year. A $3.1\sigma$ detection.
Is the detected ISW too large?

measured $\rightarrow$

simulated $\rightarrow$

(from Nadatur, Hotschkiss & Sarkar '11)
CMB lensing

On their path into our antennas, CMB photons are deflected by the gravitational potential of the large scale matter distribution, the lensing potential:

$$\psi(n) = \int_{0}^{\eta_{0} - \eta_{*}} dr \frac{r_{*} - r}{rr_{*}} (\Phi + \Psi)(\eta_{0} - r, nr)$$
CMB lensing

\[ l(l+1)C_l / 2\pi [\mu K^2] \]

\[ \Delta C_l^E / C_l \]

\( l \)

10, 100, 1000, 10^4

10^-4, 10^-2, 1, 10, 10^2

4, 0.4, 0.3, 0.2, 0.1, 0.0, -0.1, 0

1000, 2000, 3000
Conclusions

- The strongest signal of dark energy in the CMB is via its effect on the distance to the lss, $D_A(z_*)$.
- At present this is the only signal of dark energy safely (more than $5\sigma$ significance) detected in the CMB.
- One can fit the observed data perfectly well without dark energy by a simple rescaling of $D_A(z_*)$ for \( \ell > 20 \). We found $2\Delta \log \mathcal{L} = 22$ (2591 data points) for $\ell_{\text{min}} = 2$ and $2\Delta \log \mathcal{L} \lesssim 1$ for $\ell_{\text{min}} \geq 20$.
- The ISW expected for $\Lambda$CDM is detected at about $(3–4)\sigma$ by several experiments but it seems rather high.
- CMB lensing is another effect which contains information about dark energy and, especially modified gravity which will be explored in future high precision CMB experiments.

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Dark Energy, Rinberg, 2012
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