The effect of reionization on the COBE normalization

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ABSTRACT

We point out that the effect of reionization on the microwave anisotropy power spectrum is not necessarily negligible on the scales probed by COBE. It can lead to an upward shift of the COBE normalization by more than the one-sigma error quoted ignoring reionization. We provide a fitting function to incorporate reionization into the normalization of the matter power spectrum.

Key words: cosmology: theory — cosmic microwave background

1 INTRODUCTION

One of the most important uses of the COBE observations of large-angle cosmic microwave background anisotropies (Smoot et al. 1992; Bennett et al. 1996) is to normalize the power spectrum of matter fluctuations in the Universe. Accordingly, several papers have been written quoting fitting functions for this normalization as a function of various cosmological parameters. Because COBE only probes scales larger than the horizon at last scattering, it is insensitive to parameters governing physical processes within the horizon, such as the Hubble parameter $h$ and the baryon density $\Omega_B$. It does however depend on the matter density $\Omega_\Lambda$, the cosmological constant density $\Omega_\Lambda$, the spectral index (tilt) of density perturbations $n$ and the presence of gravitational waves (usually parametrized by a quantity $r$). Existing literature has provided fitting functions for spatially-flat models and open models including tilt (Bunn & White 1997), and for spatially-flat models with both tilt and gravitational waves (Bunn, Liddle & White 1996).

There is however one other parameter which can significantly alter the normalization, which is the optical depth $\tau$ for rescattering of microwave photons at lower redshift. The absence of absorption by neutral hydrogen in quasar spectra, the Gunn–Peterson effect (Gunn & Peterson 1965; see also Steidel & Sargent 1987; Webb 1992), tells us that the Universe must have reached a high state of ionization by the time of last scattering, and the presence of gravitational waves (usually parametrized by a quantity $r$). Existing literature has provided fitting functions for spatially-flat models and open models including tilt (Bunn & White 1997), and for spatially-flat models with both tilt and gravitational waves (Bunn, Liddle & White 1996).

The effect of reionization on the matter power spectrum in the Universe is not necessarily negligible on the scales probed by COBE. It can lead to an upward shift of the COBE normalization by more than the one-sigma error quoted ignoring reionization. We provide a fitting function to incorporate reionization into the normalization of the matter power spectrum.
Figure 1. Optical depth for instantaneous reionization at reionization redshift $z_{\text{reion}}$. From top to bottom the curves are $\Omega_0 = 0.3$, 0.6 and 1. We took $\Omega_B h^2 = 0.02$ and $h = 0.65$.

per cent. This is equivalent to a shift in the radiation angular power spectrum of just under 20 per cent.

2 CORRECTING THE NORMALIZATION FOR REIONIZATION

We consider only spatially-flat cosmologies, as significantly open models are now excluded (Jaffe et al. 2000). The COBE normalizations are readily obtained from the publicly-available CAMBFAST (Seljak & Zaldarriaga 1996) and CAMB programs (Lewis, Challinor & Lasenby 2000). Figure 2 shows a series of curves with varying optical depth, where the normalization of the matter power spectrum has been kept fixed, focusing on the region relevant to the COBE observations. The other cosmological parameters are those of the favoured low-density flat model with $\Omega_0 = 0.3$, $n = 1$, $h = 0.65$, $\Omega_B h^2 = 0.02$ and no gravitational waves. To a first approximation, normalizing to COBE will shift the curves to the same amplitude at $\ell \approx 10$. We use the power spectrum normalizations output from the code, which are computed by fitting a quadratic to the $C_\ell$ spectrum and implementing a fitting function from Bunn & White (1997).

Figure 2 shows two separate physical effects in operation. On the right-hand side of the plot we mainly observe the effect of reionization damping erasing the initial anisotropies, a process described in detail by Hu & White (1997); there is also some regeneration of anisotropies on those scales from the Doppler effect in scattering from the reionized electrons. Bearing in mind that the COBE normalization is particularly sensitive to multipoles around $\ell = 10$, for low $\tau$ the damping is the dominant effect in altering the power spectrum normalization.

A more interesting effect is the rise of the multipoles, including the lowest, as the optical depth is increased, an effect which reaches 10 per cent for $C_2$ at $\tau = 0.5$. The effect has a subtle origin. There are contributions to the anisotropies both from the original last-scattering surface and from the reionization scattering surface. Between recombination and reionization large-scale perturbations (i.e. those with comoving wavenumbers much less than the Hubble scale) cannot evolve, but smaller scale ones can. A given $C_\ell$ actually receives contributions from quite a wide range of comoving wavenumbers, so that the low multipoles exhibit some sensitivity to what is happening on smaller scales and this results in the increase in power. Although the effect is not large, it is significant at the level of the COBE normalization, and once $\tau$ exceeds around 0.3 the rise in the radiation power spectrum from newly-generated anisotropies actually becomes more important than the effect of reionization damping.

In Figure 3, we plot the change in the COBE normalization of the matter power spectrum as a function of $\tau$ for various choices of $\Omega_0$. The quantity $\delta_H$, defined as in Bunn et al. (1996) and Bunn & White (1997), measures the dispersion of the matter distribution, and the COBE normalization of it has a statistical error of 7 per cent. The power spectrum normalization goes as $\delta_H^2$. We see that the reionization has a significant effect on the normalization, corresponding to roughly a one-sigma shift for a wide range of optical depths. For low optical depths the reionization damping dominates and the normalization increases, reaching a maximum at $\tau \approx 0.3$. As $\tau$ increases further the reionization damping moves to smaller angular scales and becomes less significant at $\ell \approx 10$ than the regenerated anisotropies, and the normalization begins to fall.

As seen in Figure 3, there is a weak dependence on $\Omega_0$, and indeed there are similar dependences on the parameters $h$ and $\Omega_B$. The dependences arise because these parameters alter the reionization redshift, and hence characteristic angular size, corresponding to a given optical depth. The effect of varying these parameters is typically at the one or two percent level, hence much smaller than the effect of the optical depth.

There is no point in trying to fit the dependence of the reionization correction on $h$ and $\Omega_B$, since published normalizations ignore the effect of these parameters in the case with no reionization as it is well within the statistical error from cosmic variance. Equally, although quoted fitting functions do give a dependence on $\Omega_0$, the additional $\Omega_0$ dependence * We are indebted to Matias Zaldarriaga for correspondence on this issue.
of the reionization correction is at the same level (one or two percent) as those ignored effects, and so there is no incentive to try to include it either. Therefore, to sufficient accuracy one can ignore the dependence of the normalization on parameters other than \( \tau \), and the correction to the normalization can then be expressed via a \( \tau \)-dependent fitting function. We chose to fit for \( \Omega_0 = 0.4 \) as it lies roughly centrally amongst the models we studied and is close to the currently favoured value. A good fit is given by the form

\[
\frac{\delta H(\tau)}{\delta H(\tau = 0)} = 1 + 0.76\tau - 1.96\tau^2 + 1.46\tau^3, \tag{3}
\]

as shown in Figure 3, which is reliable up to \( \tau \) of 0.5. This correction can be applied to equation (29) in Bunn & White (1997) and to equations (15), (A4) and (A5) in Bunn et al. (1996); note that these fitting functions have quoted fit errors of up to 3 per cent though they are usually within 1 per cent. Even allowing for possible variation of other parameters including \( \Omega_0 \), the fit error for our correction is within 2 per cent which, given the error in the COBE normalization, should be more than adequate for the foreseeable future.

3 SUMMARY

We have quantified the effect of reionization on the COBE normalization of the matter power spectrum. For values of the optical depth in the centre of the currently-allowed region, reionization leads to a significant enhancement of the COBE-normalized matter power spectrum, which should be accounted for in attempts to constrain cosmological parameters by combining other data sets with the COBE normalization. [The effect is of course automatically included in analyses which simultaneously fit cosmic microwave background data and other data, except that most such analyses have not so far included reionization, an exception being Tegmark et al. (2000).]

We have provided a simple fitting function which allows this correction to be incorporated into published fitting functions.

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REFERENCES

Bennett C. L. et al., 1996, ApJ, 464, L1
Bunn E. F., Liddle A. R., White M., 1996, Phys. Rev. D, 54, 5917
Bunn E. F., White M., 1997, ApJ, 480, 6
Griffiths L. M., Barbosa D., Liddle A. R., 1999, MNRAS, 308, 854
Gunn J. E., Peterson, B. A., 1965, ApJ, 142, 1633
Haiman Z., Knox L., 1999, astro-ph/9902311
Hu W., White M., 1997, ApJ, 479, 568
Jaffe A. H. et al., 2000, astro-ph/0007339
Lewis A., Challinor A., Lasenby A., 2000, ApJ, 538, 473
Seager S., Sasselov D. D., Scott D., 2000, ApJSupp, 128, 407
Seljak U., Zaldarriaga M., 1996, ApJ, 469, 437
Smoot G. F. et al., 1992, ApJ, 396, L1
Steidel C. C., Sargent W. L. W., 1987, ApJ, 318, L11
Tegmark M., Zaldarriaga M., Hamilton A. J. S., 2000, astro-ph/0008167
Webb J. K., 1992, MNRAS, 255, 319

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