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Article (Published Version)

Griffiths, Louise M and Liddle, Andrew R (2001) The effect of reionization on the COBE normalization. Monthly Notices of the Royal Astronomical Society, 324 (3). pp. 769-771. ISSN 0035-8711

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Mon. Not. R. Astron. Soc. **324**, 769–771 (2001)

The effect of reionization on the *COBE* normalization

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Accepted 2001 February 3. Received 2001 January 11

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 1σ error quoted, ignoring reionization. We provide a fitting function to incorporate reionization into the normalization of the matter power spectrum.

Key words: cosmic microwave background – cosmology: theory.

1 INTRODUCTION

One of the most important uses of the Cosmic Background Explorer (*COBE*) observations of large-angle cosmic microwave background (CMB) 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 the parameters governing physical processes within the horizon, such as the Hubble parameter h and the baryon density Ω_B. It does however depend on the matter density Ω_0, the cosmological constant density Ω_Λ, 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 the 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 that can significantly alter the normalization, which is the optical depth τ, for the rescattering of microwave photons at a lower redshift. The absence of absorption by neutral hydrogen in the 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 redshift of the most distant known quasars, around 5. Scattering from the created free electrons predominantly has the effect of damping out the primary anisotropies, and the requirement that the observed peak at $\ell \sim 200$ is not destroyed sets an upper limit on the optical depth. Griffiths, Barbosa & Liddle (1999) obtained a limit of around $\tau \lesssim 0.4$ for the most plausible cosmological parameters; including new CMB data from BOOMERanG-98 and MAXIMA-1, plus other non-CMB constraints, can strengthen this somewhat (Tegmark, Zaldarriaga & Hamilton 2001). In addition to the damping, the rescattering generates a modest amount of new anisotropy via the Doppler effect.

Several mechanisms for reionization, which require a source of ultraviolet photons, have been discussed, and are extensively reviewed by Haiman & Knox (1999). In the two most popular models, the sources are massive stars in the first generation of galaxies, or early generations of quasars. Calculations are sufficiently uncertain as to give no clear guidance as to where within the currently allowed range reionization might have occurred. Assuming spatial flatness and instantaneous full reionization at redshift $z_{\rm ion}$, the optical depth is related to the redshift of reionization by (e.g. Griffiths et al. 1999)

$$\tau(z_{\rm ion}) = \frac{2\tau^*}{3\Omega_0}\left\{\left[1-\Omega_0+\Omega_0(1+z_{\rm ion})^3\right]^{1/2}-1\right\}, \qquad (1)$$

where

$$\tau^* = \frac{3cH_0\Omega_B\sigma_T}{8\pi G m_p}\times 0.88 \simeq 0.061\Omega_B h. \qquad (2)$$

Sample curves are shown in Fig. 1. We should expect τ to lie anywhere between about 0.02 and 0.4.

We note that this does not include the contribution to the optical depth of the residual ionization left over after recombination, which for typical cosmological parameters is about 0.001 and which can contribute a further optical depth of a few per cent between $z_{\rm ion}$ and $z_{\rm rec}$ (Seager, Sasselov & Scott 2000).

Because the rescattering happens at low redshifts, it can affect the microwave anisotropies on much larger angular scales than can causal processes at last scattering. The normalization of the power spectrum from *COBE* is primarily from multipoles with $\ell \sim 10$, and because the normalization is so accurate, it turns out that reionization can lead to a significant effect. We shall concentrate on the fitting functions quoted by Bunn & White (1997) and Bunn et al. (1996), whose quoted error on the dispersion δ_H, is 7 per cent statistical, with fit and other systematics bringing this up to 9 per cent. This is equivalent to a shift in the radiation angular power spectrum of just under 20 per cent.

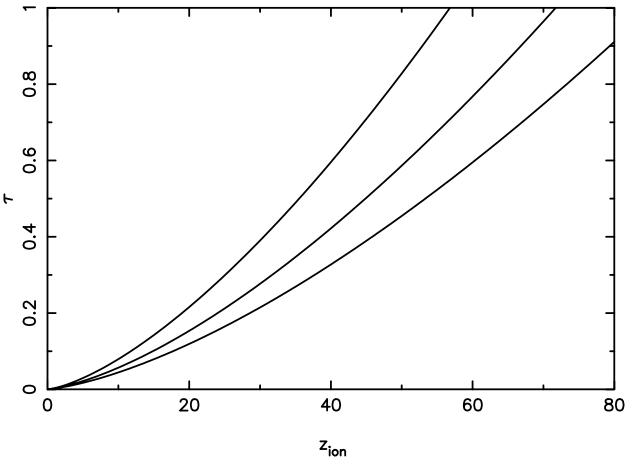

Figure 1. Optical depth for the instantaneous reionization at redshift $z_{\rm ion}$. From top to bottom the curves are $\Omega_0 = 0.3$, 0.6 and 1. We took $\Omega_{\rm B}h^2 = 0.02$ and $h = 0.65$.

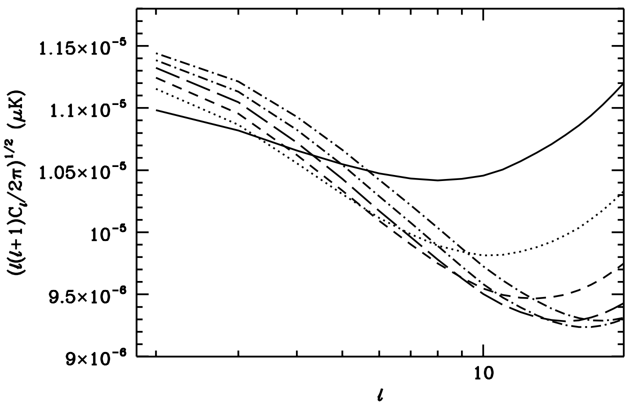

Figure 2. A set of C_ℓ curves for the standard cosmology, showing (from bottom to top on the left-hand edge) optical depths $\tau = 0$, 0.1, 0.2, 0.3, 0.4 and 0.5.

2 CORRECTING THE NORMALIZATION FOR REIONIZATION

We consider only spatially flat cosmologies, as significantly open models are now excluded (Jaffe et al. 2001). The *COBE* normalizations are readily obtained from the publicly available CMBFAST (Seljak & Zaldarriaga 1996) and CAMB programs (Lewis, Challinor & Lasenby 2000). Fig. 2 shows a series of curves with a 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 $\Omega_0 = 0.3$, $n = 1$, $h = 0.65$, $\Omega_{\rm B}h^2 = 0.02$, and no gravitational waves. To a first approximation, normalizing to *COBE* will shift the curves to the same amplitude at $\ell \simeq 10$. We use the power spectrum normalizations output from the code, which are computed by fitting a quadratic to the C_ℓ spectrum and implementing a fitting function from Bunn & White (1997).

Fig. 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 the scattering from the reionized electrons. Bearing in mind that the *COBE* normalization is particularly sensitive to multipoles around $\ell = 10$, for low τ the damping is the dominant effect in altering the power spectrum normalization.

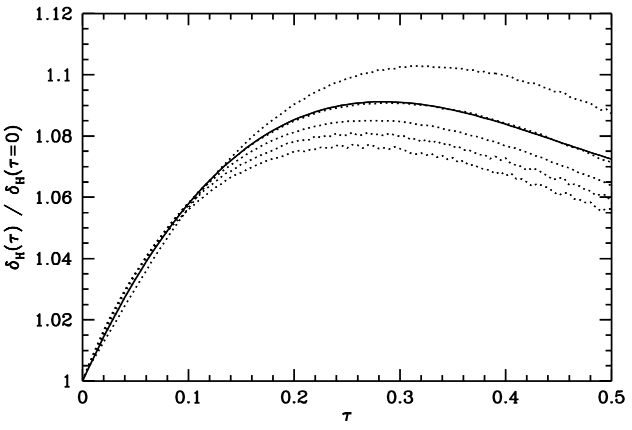

Figure 3. The *COBE* normalization as a function of τ is shown by the dashed lines for (from top to bottom) $\Omega_0 = 0.2$, 0.4, 0.6, 0.8 and 1.0. The solid line shows the fit quoted in equation (3).

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 the 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_ℓ 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 τ 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 Fig. 3, we plot the change in the *COBE* normalization for the matter power spectrum as a function of τ for various choices of Ω_0. The quantity $\delta_{\rm H}$, 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 behaves as $\delta_{\rm H}^2$. We see that the reionization has a significant effect on the normalization, corresponding to roughly a 1σ shift for a wide range of optical depths. For low optical depths the reionization damping dominates and the normalization increases, reaching a maximum at $\tau \simeq 0.3$. As τ increases further, the reionization damping moves to smaller angular scales and becomes less significant at $\ell \simeq 10$ than the regenerated anisotropies, and the normalization begins to fall.

As seen in Fig. 3, there is a weak dependence on Ω_0, and indeed there are similar dependences on the parameters h and $\Omega_{\rm B}$. The dependences arise because these parameters alter the reionization redshift, and hence the characteristic angular size, corresponding to a given optical depth. The effect of varying these parameters is typically at the 1 or 2 per cent 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 $\Omega_{\rm B}$, 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 Ω_0, the additional Ω_0 dependence of the reionization correction is at the same level (1 or 2 per cent) as those ignored effects, and so there is no incentive to try to include it either. Therefore, to a sufficient accuracy one can ignore the dependence of the normalization on parameters other than τ, and the correction to the normalization can then be expressed via a τ-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

$$\frac{\delta_{\mathrm{H}}(\tau)}{\delta_{\mathrm{H}}(\tau=0)} = 1 + 0.76\tau - 1.96\tau^2 + 1.46\tau^3, \qquad (3)$$

as shown in Fig. 3, which is reliable up to $\tau = 0.5$. 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 Ω_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 the analyses which simultaneously fit the CMB data and other data, except that most such analyses have not so far included reionization, an exception being Tegmark et al. (2001).]

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

ACKNOWLEDGMENTS

LMG was supported by PPARC. We thank Antony Lewis and Matias Zaldarriaga for clarifying discrepancies between the CAMB and CMBFAST codes, and Matias Zaldarriaga for providing a patch. We further thank Matias Zaldarriaga for important correspondence on the low-ℓ behaviour in reionized models.

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