CONSTRANTS ON THE REDSHIFT OF REIONIZATION FROM CMB DATA

JENS SCHMALZING, JESPER SOMMER-LARSEN, AND MARTIN GÖTZ

1 In order to constrain the redshift of reionization $z_{\text{re}}$, this becomes possible by combining the CMB data with cosmological parameters from various independent measurements, including Big Bang Nucleosynthesis (BBN) and X-ray cluster data. Most notably, our results provide a robust lower bound on $z_{\text{re}}$. We find that $z_{\text{re}} > 15$ (8) at the 68% (95%) confidence level, unless the Hubble constant is larger than 75 km s$^{-1}$Mpc$^{-1}$.

Subject headings: Methods: statistical — cosmic microwave background — Cosmology: observations — early Universe — large-scale structure of Universe

1 INTRODUCTION

In CDM cosmologies the first baryonic objects form at redshifts as high as 50 (see, e.g., Haiman et al. 1996 and references therein). At some lower redshift $z_{\text{re}}$, the formation of these and subsequent baryonic objects leads to the reionization of the universe by the combined effects of the fairly hard UV radiation from AGNs and the softer UV radiation from young, star-bursting galaxies and possibly also from a population of early, more uniformly distributed stars (the putative population III stars). Typical estimates of $z_{\text{re}}$ for CDM models lie in the range $z_{\text{re}} \sim 10 - 20$ (Haiman & Loeb 1998).

Recently, various problems with CDM on galactic scales have lead to the proposal that dark matter is “warm” rather than “cold” (Moore et al. 1999; Hogan 1999; Sommer-Larsen & Dolgov 1999 and references therein). In WDM models the redshift of formation of the first baryonic objects is smaller than for CDM and increasingly so with decreasing WDM particle mass. It obviously still provides an upper limit to the redshift of reionization. Observational lower limits on the redshift of reionization can therefore be used to place lower limits to the mass of the putative warm dark matter particles.

Spectral observations of quasars at $z \lesssim 5$ show evidence for a relatively early epoch of reionization. The lack of complete absorption shortward of the Ly$\alpha$ line (the so-called Gunn-Peterson effect; Gunn & Peterson 1965) implies $z_{\text{re}} \gtrsim 4 - 5$, possibly even $z_{\text{re}} > 5.8$ (Fan et al. 2000).

Constraints on $z_{\text{re}}$ can also be obtained from data on anisotropies of the cosmic microwave background (CMB) radiation (Griffiths et al. 1999). Compton scattering of CMB photons on free electrons leads to the suppression of the primary anisotropies on small and intermediate angular scales and hence a characteristic change of the angular power-spectrum $C_\ell$.

So far the CMB data have been used to place upper limits on the redshift of reionization $z_{\text{re}} \lesssim 30$ (Griffiths et al. 1999). In this Letter we use the Maxima-1 and combined Boomerang and Maxima-1 data (Hanany et al. 2000; Jaffe et al. 2000) to place astrophysically interesting upper and lower limits on $z_{\text{re}}$. The Letter is organized as follows: In Section 2, we motivate the choice of a number of cosmological parameters prior to analyzing the CMB data. Section 3 briefly explains our method of analysis, the results of which are summarized in Section 4. Section 5 discusses those results and provides an outlook.

2 COSMOLOGICAL PARAMETERS

Apart from the redshift of reionization that we are interested in, a cosmological model is specified by a number of other parameters. Unfortunately, today’s CMB measurements alone still provide rather broad constraints on them when they are jointly taken into account (an extreme example of the astonishing consequences can be found in Figure 1 of Tegmark et al. 2000). To obtain meaningful results, one has to use other observational data, or one’s own prejudice, to fix some of the parameters beforehand.

To begin with, we have to specify what sort of energy is present in the Universe. Usually, one takes into account five different kinds, namely vacuum energy $\Omega_\Lambda$, space curvature $\Omega_k$, baryonic matter $\Omega_b$, hot dark matter $\Omega_{\text{HDM}}$, and cold dark matter $\Omega_{\text{CDM}}$, where the values denoted by $\Omega$ are the energy densities of the respective type relative to the critical density. On the basis of standard inflationary theory we assume that there is no space curvature, $\Omega_k = 0$, and also that the initial power spectrum is scale invariant and no tensor modes are present (see, however, the discussion in Section 5). Furthermore, dark matter shall be cold or warm, $\Omega_{\text{HDM}} = 0$, since the effect of massive neutrinos will be negligible on the angular power spectrum of the CMB (Dodelson et al. 1996) – but see below. Obviously, this means that only three types of energy remain in the Universe. They are linked via the relation $\Omega_\Lambda + \Omega_{\text{CDM}} + \Omega_b = 1$.

The density in baryons $\Omega_b$ can be constrained rather nicely using Big Bang Nucleosynthesis (BBN). Taking into account a broad range of recent measurements (Tytler et al. 2000), it seems reasonable to set the value of $\Omega_b h^2$ to $0.019 \pm 0.002$, where $h$ denotes the Hubble constant.
measured in units of 100 km s\(^{-1}\) Mpc\(^{-1}\).

Furthermore, measurements on bright X-ray clusters (Ettori & Fabian 1999) provide a robust estimate of the baryonic fraction \(f_b\), the ratio of gas to total matter in clusters. Both observations (Bahcall et al. 1995) and simulations (White et al. 1993; Evrard 2000) suggest that this is more or less equal to the fraction of baryons versus all matter in the whole Universe. Translated into our cosmological parameters, we have

\[
f_b = \frac{\Omega_b \Omega_{\text{CDM}}}{\Omega_b + \Omega_{\text{CDM}}} = (0.069 \pm 0.012)h^{-3/2} + 0.04. \tag{1}
\]

Finally, the Hubble constant is taken to be \(h = 0.65 \pm 0.10\), as a plausible compromise between various recent estimates (Perlmutter et al. 1999; Mould et al. 2000; Reese et al. 2000; Patel et al. 2000; Freedman 2000 and references therein).

The possible contribution to the dark matter density from massive neutrinos with free-streaming mass scale much larger than the mass of large clusters of galaxies would not be accounted for by this method. Because of the small mass of such neutrinos (\(\lesssim 1\) eV), the contribution to \(\Omega_{\text{DM}}\) can be neglected. That \(\Omega_{\text{DM}} \ll 1\) is also a possible interpretation of the Super-Kamiokande atmospheric neutrino data, as discussed by Tegmark et al. (2000).

3. METHOD

Recently, Hanany et al. (2000) published a measurement of the power spectrum of the CMB from a highly resolved patch of the sky. We use their published data throughout. We have also used the combined Boomerang and Maxima data of Jaffe et al. (2000) for our analysis and have obtained results very similar to the ones presented here.

The measured CMB data consists of ten estimates of the power spectrum \(C_{\ell}\) averaged over a certain \(\ell\) range. In order to compare the measured CMB data to a given cosmological model, we first calculate a numerical spectrum with CMBFAST (Seljak & Zaldarriaga 1996). The model spectrum is then binned in the same way as the observed data, and the resulting averages compared to the data by calculating \(\chi^2\). For measurements following Gaussian statistics, we have

\[
\chi^2 = \sum_{i=1}^{10} \left( \frac{\Delta_i^{(\text{data})} - \Delta_i^{(\text{model})}}{\sigma_i} \right)^2, \tag{2}
\]

where \(\Delta_i^{(\text{data})}\) and \(\Delta_i^{(\text{model})}\) denote the average power in the \(i\)th bin for the Maxima data and the given model, respectively, and \(\sigma_i\) is the measurement error of the data point. Actually, the probability distribution function of power spectrum measurements is slightly skewed in comparison to a Gaussian, so we correct for this effect with the offset lognormal method by Knox et al. (1998); Bond et al. (2000).

Assuming that the individual power measurements are independent, a confidence level of 68\% corresponds to a \(\chi^2\) of less than 11.5, while a \(\chi^2\) of 18.3 or more allows to reject a model at the 95\% confidence level. Therefore, we always show the contours of these \(\chi^2\) values below. To put it simply, we ask the question “Which models fit well?”

Normally, however, one does not perform this simple \(\chi^2\) analysis. Instead, errors are assigned to fitted parameters by maximum likelihood. Most importantly, this means that the error is determined in comparison to the best fit, and will in general be smaller. Again, one can summarize this approach in a simple question: “Which model fits best?”

4. RESULTS

When we apply all the constraints mentioned in Section 2, the only cosmological parameter that remains free is actually the redshift of reionization \(z_{\text{re}}\). From the \(\chi^2\) analysis, we obtain a confidence interval of \(18 < z_{\text{re}} < 25\) at a level of 68\% and a range of \(16 < z_{\text{re}} < 29\) at 95\% confidence. Figure 1 compares the data themselves and the model that provides the best fit. This fit is clearly acceptable, having a \(\chi^2\) of 8.3 for ten degrees of freedom.

As explained above, we use various observational constraints on cosmological parameters. To illustrate the effect of errors in their measurement on our results, we subsequently omit each of them in turn. This means that we have a second free parameter, in addition to the redshift of reionization.

In order to illustrate the methodical point made in Section 3, in Figures 2, 3, and 4 we also show the confidence regions obtained from maximum likelihood analysis. It is interesting to see how much smaller they are compared to the regions obtained from the \(\chi^2\) values. We interpret this as an indication that one should be cautious and use the larger regions, in order to not rule out perfectly valid models.

Figure 2 and Figure 3 display the constraints on the redshift of reionization obtained when the baryon density \(\Omega_b h^2\) and the baryon fraction \(f_b\), respectively, are allowed to vary. Of course, this variation somewhat broadens the allowed redshift range. However, the change is not very large, in either case the lower bounds on \(z_{\text{re}}\) go down to 17 and 13 for the 68\% and 95\% confidence level, respectively.

The situation changes somewhat when we let the Hubble constant vary around the adopted value of \(h = 0.65\). Figure 4 shows the results. Despite the rather large uncertainty of \(h\), we can still constrain \(z_{\text{re}}\): Unless \(h > 0.75\), which seems unlikely when combining various methods of Hubble parameter estimation, we can conclude that \(8 < z_{\text{re}} < 32\) at the 2\(\sigma\)-level, and at the 1\(\sigma\)-level we find that \(15 < z_{\text{re}} < 27\).

5. DISCUSSION AND OUTLOOK

We have used the Maxima measurements of the angular power spectrum of the CMB to constrain the redshift of reionization \(z_{\text{re}}\). We found that astrophysically interesting bounds can be found when one constrains the allowed range of cosmological parameters with other observations, including Big Bang Nucleosynthesis and X-ray cluster data. Even when the possible uncertainties of these parameters were taken into account, we still obtained a robust estimate \(8 < z_{\text{re}} < 32\) at the 95\% confidence level, unless \(h > 0.75\). The implications of this result for structure formation theory and the mass of the putative warm dark matter particle will be discussed in a forthcoming paper.

One caveat is our omission of the possible contribution from tensor modes: tensor modes (gravity waves) contribute extra power on super-degree scales (\(\ell < 100\)), so that when the total power (scalar and tensor modes) is normalized at low \(\ell\), the scalar modes become lower and thus
the high-$\ell$ power looks suppressed. That effect is similar to that of reionization, but fortunately this degeneracy can be broken with future observations of the polarization angular power spectrum. For an electron scattering optical depth of $\tau = 0.1$ – corresponding to $z_{re} \approx 13$ for standard cosmological parameters – the polarization signal should be easily detectable by the MAP and Planck missions (Bennett et al. 1995; Bersanelli et al. 1996), and possibly also the forthcoming new Maxima and Boomerang missions.

ACKNOWLEDGMENTS

We have benefited from discussions with Per Rex Christensen, Gus Evrard, Pavel Naselsky, and Joe Silk. This work was supported by Danmarks Grundforskningsfond through its support for TAC.

REFERENCES

Bahcall, N. A., Lubin, L. M., & Dorman, V. 1995, ApJ, 447, L81
Bennett, C. L. et al. 1995, BAAS, 187, 1385
Bersanelli, M. et al. 1996, COBRAS/SAMBA. A mission dedicated to imaging the anisotropies of the cosmic microwave background. Report on the phase A study (European Space Agency)
Bond, J. R., Jaffe, A. H., & Knox, L. 2000, ApJ, 533, 19
Dodelson, S., Gates, E., & Stebbins, A. 1996, ApJ, 467, 10
Ettori, S. & Fabian, A. C. 1999, MNRAS, 305, 854
Evrard, A. E. 2000, private communication
Fan, X. et al. 2000, submitted to AJ, astro-ph/0005414
Freedman, W. L. 2000, Physics Rep., 333-334, 13
Griffiths, L. M., Barbosa, D., & Liddle, A. R. 1999, MNRAS, 308, 854
Gunn, J. E. & Peterson, B. A. 1965, ApJ, 142, 1633
Haiman, Z. & Loeb, A. 1998, ApJ, 503, 505
Haiman, Z., Rees, M., & Loeb, A. 1996, ApJ, 467, 522
Hanany, S. et al. 2000, submitted to ApJ, astro-ph/0005123
Hogan, C. 1999, astro-ph/9912549
Jaffe, A. H. et al. 2000, submitted to PRL, astro-ph/0007333
Knox, L., Bond, J. R., Jaffe, A. H., Segal, M., & Charbonneau, D. 1998, Phys. Rev. D, 58, 083004
Moore, B., Ghinga, S., Governato, F., Lake, G., Quinn, T., Stadel, J., & Tozzi, P. 1999, ApJ, 524, L19
Mould, J. R. et al. 2000, ApJ, 529, 786
Patel, S. K. et al. 2000, ApJ, 541, 37
Perlmutter, S. et al. 1999, ApJ, 517, 565
Reese, E. D. et al. 2000, ApJ, 533, 38
Seljak, U. & Zaldarriaga, M. 1996, ApJ, 469, 437
Sommer-Larsen, J. & Dolgov, A. 1999, submitted to ApJ, astro-ph/9912166
Tegmark, M., Zaldarriaga, M., & Hamilton, A. J. 2000, astro-ph/0008167
Tytler, D., O’Meara, J. M., Suzuki, N., & Lubin, D. 2000, to appear in Physica Scripta, astro-ph/0001318
White, S. D. M., Navarro, J. F., Evrard, A. E., & Frenk, C. S. 1993, Nature, 366, 429
Fig. 1.— The best fit (red line) to the Maxima data (black crosses). The length of the crosses' arms in the $x$- and $y$-direction indicate the width of the $\ell$ range and the measurement errors of the power, respectively.
Fig. 2.— Likelihood contours for varying baryon density $\Omega_b h^2$. The Hubble constant is fixed at $h = 0.65$ and the constraint (1) on the baryonic fraction $f_b = \frac{1}{3}$ is in effect. The solid blue lines indicate the one- and two-sigma error regions determined from the $\chi^2$ values. The dotted red lines show the same for the maximum likelihood analysis. The shaded bar indicates the observational 1σ range of $\Omega_b h^2$ obtained using BBN.
Fig. 3.— Likelihood contours for varying baryonic fraction $f_b$. The Hubble constant is $h = 0.65$ again, but now $\Omega_b h^2$ is fixed at 0.019. Line styles are the same as in the previous Figure.
Fig. 4.— Likelihood contours for varying Hubble constant. Both $f_b$ and $\Omega_b h^2$ are now constrained as explained in Section 2. Again, solid blue and dotted red lines indicate the error regions for the $\chi^2$ analysis and the maximum likelihood method, respectively.