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DELAYED RECOMBINATION

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ABSTRACT

Under the standard model for recombination of the primeval plasma and the cold dark matter model for structure formation, recent measurements of the first peak in the angular power spectrum of the cosmic microwave background temperature indicate that the spatial geometry of the universe is nearly flat. If sources of Lyα resonance radiation, such as stars or active galactic nuclei, were present at $z \sim 1000$ they would delay recombination, shifting the first peak to larger angular scales and producing a positive bias in this measure of space curvature. It can be distinguished from space curvature by its suppression of the secondary peaks in the spectrum.

Subject heading: cosmic microwave background

1. INTRODUCTION

The measurements of the anisotropies of the cosmic microwave background (CMB) offer extraordinarily powerful tests of the relativistic Friedmann-Lemaître cosmological model and the nature of the early stages of cosmic structure formation (e.g., Jungman et al. 1996). Indeed, the recent detection of the first peak in the angular power spectrum of the CMB temperature indicates that space is close to flat (Miller et al. 1999; Melchiorri et al. 1999; de Bernardis et al. 2000; Hanany et al. 2000). The interpretation is quite indirect, however, so we must seek diagnostics for possible complications.

Because relatively few physical effects can *increase* the angular scale of the first peak, its observed large scale is believed to strongly disfavor open universes. Of the fundamental cosmological parameters, only a Hubble constant well in excess of observations can substantially increase the scale of the peak in an open or flat universe (Hu & Sugiyama 1995).

One possibility is that some process at redshift $z \sim 1000$ delayed recombination of the primeval plasma. This would increase the sound horizon at last scattering and decrease the angular size distance to last scattering, moving the first peak of the CMB temperature fluctuation spectrum to smaller angular wavenumber (Hu & White 1996; Weller, Battye, & Albrecht 1999) and biasing the measure of space curvature to an apparent value that is too large (more positive). Delayed recombination also would suppress the secondary peaks by increasing the time for acoustic oscillations to dissipate (Silk 1968; Hu & White 1996).

Because the first peak is not observed to have suffered substantial dissipation, recombination in the delayed model must be rapid compared to the cosmological expansion rate. Thus, if recombination were delayed by ionizing radiation from decaying dark matter (e.g., Sarkar & Cooper 1983; Scott, Rees, & Sciama 1991; Ellis et al. 1992) or evaporating primeval black holes (Nasel'skij & Polonarëv 1987) or by thermal energy input from cosmic string wakes (Weller et al. 1999), the source would have to terminate quite abruptly and well before $z \sim 100$ when the universe starts to become optically thin even when fully ionized.

Here we consider a picture that more naturally allows rapid recombination: sources of radiation at $z \sim 1000$ with a prominent Lyα resonance line. The Lyα photons would increase the population in the principal quantum number $n = 2$ levels of atomic hydrogen, increasing the rate of photoionization from $n = 2$ by the CMB. Since the rate of thermal photoionization from $n = 2$ varies rapidly with redshift at $z \lesssim 1000$, the delayed recombination can be rapid. Rapid recombination also requires that the sources produce far fewer ionizing photons than Lyα photons, and to avoid perturbing the CMB frequency spectrum the energy in optical radiation must not be much more than 100 times that in the line. Under these conditions, the residual ionization is small enough that the optical depth for Thomson scattering after recombination is well below unity, so the height of the first peak in the spectrum of CMB temperature fluctuations is little affected by the delayed recombination. The shift in the angular wavenumber at the first peak is modest also, even if early sources produce many Lyα photons per baryon, but the shift can be considerably larger than the projected precision of the measurements. Thus, it is fortunate that we seem to have an unambiguous diagnostic for delayed recombination in the suppression of the secondary peaks.

After this work was substantially complete, we learned that the BOOMERANG and MAXIMA experiments favor a substantial suppression of the second peak (de Bernardis et al. 2000; Hanany et al. 2000), consistent with our model. We emphasize that there are many other ways to account for this effect and that within the conventional adiabatic cold dark matter (CDM) model the recombination history is well understood (Seager, Sasselov, & Scott 2000 and earlier references therein). Also, we are impressed by the extreme to which we had to go to find a viable correction to the commonly assumed relation between the cosmology and the residual angular fluctuations in the CMB: our hypothetical early sources of Lyα radiation are not at all natural. But the interpretation of the CMB fluctuations involves a wonderfully large extrapolation of well-established physics and phenomenology, and it is good science to bear in mind the possibility that Nature is more complicated than our ideas.

2. THE MODEL

Since the early source of radiation is purely conjectural, a simple model is appropriate. We assume that the rate of production of Lyα resonance photons per unit volume (in excess of those produced by the primeval plasma) is

$$dn_\alpha/dt = \epsilon_\alpha n_{\rm H} H(t), \tag{1}$$

where $n_{\rm H}$ is the number density of hydrogen nuclei, $H(t) = \dot{a}/a$ is the expansion rate, and ϵ_α is a free parameter. The com-

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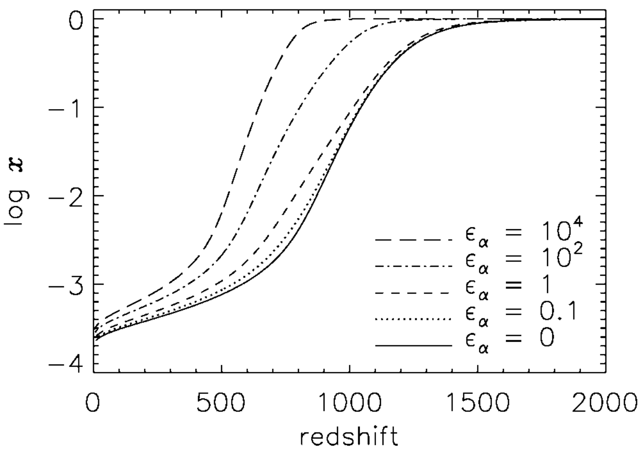

FIG. 1.—Ionization fraction x as a function of redshift for $\epsilon_i = 0$ and various values of ϵ_α.

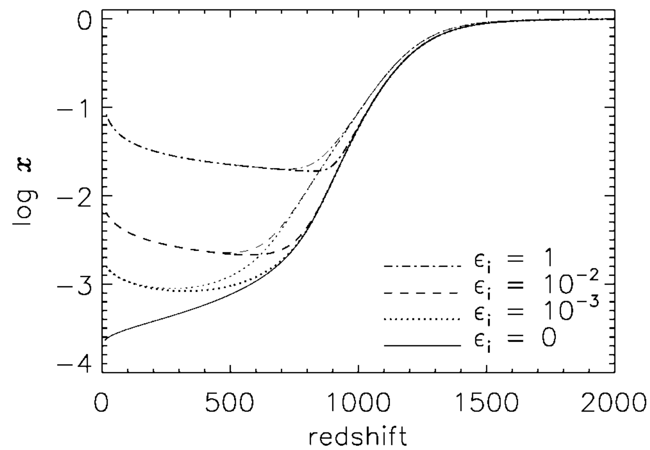

FIG. 2.—Effect of new sources of ionizing photons on the recombination history. For each value of ϵ_i, the upper curve is for $\epsilon_\alpha = 1$ and the lower curve is for $\epsilon_\alpha = 0$.

putation of the ionization history by Seager et al. (2000) is readily adjusted to take account of this new source term if it is approximately homogeneous. The results in Figure 1 assume the Hubble parameter is $h = 0.7$ in units of 100 km s^{-1} Mpc^{-1}, the baryon density parameter is $\Omega_b h^2 = 0.02$ (Tytler et al. 2000), and the total matter density parameter is $\Omega_m = 0.25$. The ionization history is quite similar at $\Omega_m = 0.4$.

The optical depth for Thomson scattering subsequent to redshift z is

$$\tau = 63x\left(\frac{1-Y_p}{0.76}\right)\left(\frac{\Omega_b h^2}{0.02}\right)\left(\frac{\Omega_m h^2}{0.122}\right)^{-1/2}\left(\frac{z}{10^3}\right)^{3/2} \qquad (2)$$

if the fractional ionization is constant at x at redshift less than z. Figure 1 shows that the delayed recombination through the redshift z_* at which τ passes through unity is about as fast relative to the expansion rate as in the standard recombination model. The decrease in z_* is approximately

$$\frac{z_*(\epsilon_\alpha)}{z_*(0)} = (1+3\epsilon_\alpha)^{-0.042}. \qquad (3)$$

Sources of Lyα photons may also produce ionizing radiation. Since the rate of recombination of fully ionized baryons at the cosmic mean density is faster than the rate of expansion, the ionization x may be approximated by the equilibrium equation $\alpha n_{\rm H} x^2 \simeq \epsilon_i H$. The definition of the parameter ϵ_i follows equation (1), and α is the recombination coefficient for principal quantum numbers $n \geq 2$. At this ionization and helium mass fraction $Y_p = 0.24$, the optical depth for Thomson scattering is

$$\tau \sim \epsilon_i^{1/2}\left(\frac{\Omega_b h^2}{0.02}\right)^{1/2}\left(\frac{\Omega_m h^2}{0.122}\right)^{-1/4}\left(\frac{z}{10^3}\right)^{1.2}. \qquad (4)$$

Figure 2 shows the effect of the production of ionizing photons on the ionization history. If $\epsilon_i \gtrsim 1$ the slow decrease in the optical depth through $\tau \sim 1$ would remove the first peak in the anisotropy power spectrum, an effect the measurements indicate is unacceptable.

If the spectra of our hypothetical sources resembled quasars, the ionizing radiation in the big blue bump would be comparable to the luminosity in the Lyα line (based on Lyα luminosity ∼5% of the luminosity below 10 eV), ϵ_α would have to be less than unity, and the effect on the CMB would be quite small. If the source spectra were softer, perhaps because shrouded by H I, the most significant constraint would be the distortion of the CMB frequency spectrum. This is parametrized by the fractional addition $\delta U/U = 4y$ to the CMB energy density. If the total source luminosity were F times the rate of energy released in the Lyα line and a fraction f were transferred to the CMB, the contribution to the Compton-Thomson parameter y per Hubble time would be

$$y = \frac{\epsilon_\alpha n_{\rm H} \hbar\omega_\alpha fF}{4(1+z)aT_o^4} \sim 10^{-9}\frac{\epsilon_\alpha fF}{z_3} \qquad (5)$$

at redshift $z = 10^3 z_3$. Since $|y| < 1.5 \times 10^{-5}$ (Fixsen et al. 1996), an order of magnitude allowance for the integral of y yields $\epsilon_\alpha fF \lesssim 10^3 z_3$. At $z_3 \lesssim 30$ the fraction f of the energy of radiation below the Lyman limit that is transferred to the CMB by Thomson scattering is the product of the Compton shift $\delta\nu/\nu \sim h\nu/mc^2$ and the optical depth[3] $\tau \sim 100xz_3^{3/2}$, giving $f \lesssim 10^{-3}z_3^{3/2}$ and $\epsilon_\alpha F \lesssim 10^6 z_3^{-1/2}$. At $\epsilon_\alpha \sim 10^3$, the largest number in Figure 3, the energy luminosity in Lyα would have to be greater than about 1% of the total at $z_3 \sim 100$ and about 1/10 of 1% at decoupling.

3. TEMPERATURE ANISOTROPY POWER SPECTRUM

In the adiabatic CDM model, the ionization history and the cosmological parameters fix the CMB anisotropy power spectrum; the results in Figure 3 for the cosmologically flat model with the parameters in Figure 1 and in Figure 4 for an open model with the cosmological parameters $\Omega_m = 0.6$, $\Omega_\Lambda = 0$, $h = 0.7$, $\Omega_b h^2 = 0.02$ are computed using a code based on White & Scott (1996).

The shift in the angular wavenumber l_1 at the peak is noteworthy because l_1 is used to infer the space curvature. A general expression for its value in adiabatic models is (Hu & Sugiyama

[3] At $z_3 \gtrsim 0.6$ lithium is thermally ionized, and at lower redshift the optical depth for photoionization of neutral lithium is below unity.

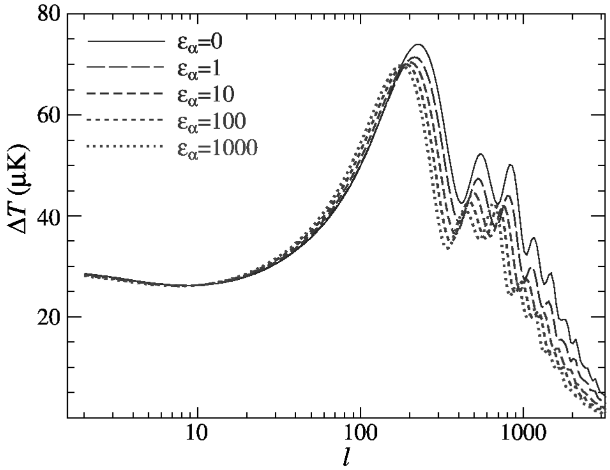

FIG. 3.—Temperature anisotropy power spectrum ($\Delta T = [l(l+1)C_l/2\pi]^{1/2}$) for various values of the Lyα production parameter ϵ_α.

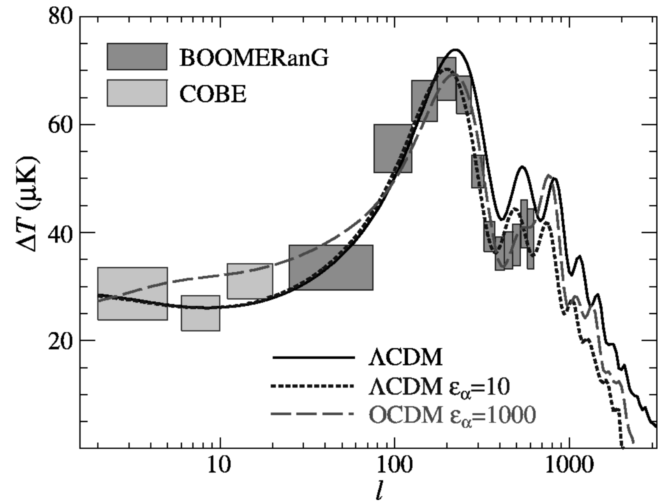

FIG. 4.—A delay in recombination (with $\epsilon_\alpha = 1000$) can make an open universe ($\Omega_m = 0.6$, *dashed line*) appear flat (*solid line*, $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$) or decrease l_1 in a flat universe and suppress the secondary peaks (with $\epsilon_\alpha = 10$). The *COBE* and BOOMERANG data are plotted with boxes representing bandwidth times 1 σ error bars.

1995; Hu et al. 2000)

$$l_1 \approx \frac{125}{\sqrt{(\Omega_m + \Omega_\Lambda)^p}}[1 + \ln(1-\Omega_\Lambda)^{0.085}]\left(\frac{z_*}{10^3}\right)^{1/2} \times \left(\frac{1}{\sqrt{R_*}}\ln\frac{\sqrt{1+R_*}+\sqrt{R_*+r_*R_*}}{1+\sqrt{r_*R_*}}\right)^{-1}, \quad (6)$$

where $p \approx (1-\Omega_\Lambda)^{-0.76}$,

$$\begin{aligned} r_* &= 0.042m^{-1}(z_*/10^3),\\ R_* &= 30b(z_*/10^3)^{-1},\\ z_*(0) &\approx 1008(1+0.00124b^{-0.74})(1+c_1 m^{c_2}),\\ c_1 &= 0.0783b^{-0.24}(1+39.5b^{0.76})^{-1},\\ c_2 &= 0.56(1+21.1b^{1.8})^{-1}, \end{aligned} \quad (7)$$

with $b \equiv \Omega_b h^2$ and $m \equiv \Omega_m h^2$. Although in isocurvature models l_1 is larger by 50% or more, it scales with cosmological parameters in the same way.

The leading-order dependence of the peak scale is then $l_1 \propto (\Omega_m + \Omega_\Lambda)^{-1/2} z_*^{1/2}$. A 10% change in z_* shifts l_1 by 5% and can compensate a 10% change in the spatial curvature $\Omega_m + \Omega_\Lambda$ near $\Omega_m = 1$. In our model for delayed recombination with z_* given by equation (3), $\epsilon_\alpha = 1000$ can make an open universe with $\Omega_m = 0.6$ appear flat (Fig. 4).

Even in the context of cosmologically flat models, one might want to consider the possibility of delayed recombination. The observed peak at $l_1 = 206 \pm 6$ (1 σ combined BOOMERANG and MAXIMA; Hu et al. 2000) favors either a slightly closed low-density universe or high physical matter density ($\Omega_m h^2$). While flat models are certainly still consistent with the data, the expected increase in precision of the measurements could force one into accepting either a closed geometry, large Hubble constant, or delayed recombination.

The amplitudes of the secondary peaks break this approximate degeneracy of delayed recombination with space curvature or the model for structure formation. While the promptness of the delayed recombination nearly preserves the first peak in the spectrum, the secondary peaks are strongly suppressed because of the extra time the photons are allowed to diffuse (Silk 1968). As discussed in Hu & White (1996), the ratio of the first peak location to the location of the damping tail is a sensitive test of delayed recombination. An equally important but more subtle effect is that a delay in recombination raises the baryon-photon momentum density ratio R_* due to the redshifting of the photons. This effect suppresses the second peak and raises the third. Although an increase in the baryon density parameter also has this effect, it simultaneously reduces rather than increases the damping and can in principle be distinguished through the higher peaks.

Under standard recombination, the ratio of power at the second versus first peak scales as

$$H_2(0) \equiv \left(\frac{\Delta T_{l_2}}{\Delta T_{l_1}}\right)^2 \approx 0.7\left[1 + \left(\frac{\Omega_b h^2}{0.016}\right)^4\right]^{-1/4} 2.4^{n-1}. \quad (8)$$

In our model, $H_2(\epsilon_\alpha) \approx H_2(0)z_*(\epsilon_\alpha)/z_*(0)$ such that delayed recombination is twice as effective in suppressing power at the second peak as it is at shifting the first peak. Observations currently suggest $H_2 = 0.38 \pm 0.04$ (Hu et al. 2000) compared with ∼0.5 in our fiducial ΛCDM model with standard recombination. Of course, the tilt n and the baryon density can also lower this ratio.

Because of its cumulative effect over the secondary peaks, ϵ_α has statistically significant effects as long as it is greater than

$$\epsilon_{\min} = \left[\sum_{l=2}^{l_{\max}}(l+1/2)\left(\frac{\partial \ln C_l}{\partial \epsilon}\right)^2\right]^{-1/2}, \quad (9)$$

where $l_{\max}$ is the largest l for which the measurements are cosmic variance limited. For $l_{\max} = 500$, $\epsilon_{\min} = 0.006$; for $l_{\max} = 1000$, $\epsilon_{\min} = 0.002$.

4. DISCUSSION

Our model for delayed recombination with $\epsilon_\alpha = 1$ shifts the first peak of the CMB fluctuation spectrum by 5% and reduces the secondary peak by 10%, observationally interesting effects.

The sources, perhaps hot stars or active galactic nuclei, must not produce much ionizing radiation (Fig. 2), perhaps because they are shrouded by envelopes of neutral primeval material, and the optical luminosity must not be more than about 100 times the energy radiated in Lyα photons. These are significant but not impossible constraints.

Our picture does not follow from the conventional CDM model for structure formation. Apparent problems with excess small-scale clustering in this model (Moore et al. 1999; Klypin et al. 1999) have motivated discussions of modifications (Spergel & Steinhardt 2000; Kamionkowski & Liddle 1999; Peebles 2000; Hu, Barkana, & Gruzinov 2000). These modifications would tend to delay the appearance of the first generation of gravitationally bound systems, however, in the opposite direction to what is postulated here. This does not rule out early sources of Lyα photons, of course, but it does suggest one might best look for effects outside the adiabatic CDM model. Perhaps cosmic strings produced wakes that were subdominant to the primeval CDM density fluctuations in determining the mass fluctuation power spectrum but did produce occasional non-Gaussian density fluctuations (Contaldi, Hindmarsh, & Magueijo 1999) large enough to have collapsed to stars or active black holes that could have produced Lyα photons.

To summarize, we have argued that the picture of delayed recombination by sources of Lyα photons has the virtue that it naturally preserves the observed first peak in the CMB temperature angular power spectrum, and it has the effect of complicating the analysis of the CMB fluctuation spectrum by shifting the peak to larger scales. The latter is an important consideration in the application of an exceedingly powerful cosmological test. The most direct diagnostic for delayed recombination seems to be the suppression of the secondary peaks in the spectrum. The amplitude of the third peak, which may be measured by a host of experiments in the coming year, is crucial for distinguishing the effect of delayed recombination from that of adjustments of the values of space curvature, the baryon density, the Hubble constant, or the shape of the spectrum of the primeval density fluctuations. If the measured secondary peaks agreed with the standard model for recombination with astronomically acceptable cosmological parameters that fit the primary peak, it would convincingly rule out our model for delayed recombination.

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