Probing the last scattering surface through recent and future CMB observations

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Abstract. We have constrained the extended (delayed and accelerated) models of hydrogen recombination, by investigating associated changes of the position and the width of the last scattering surface. Using the recently obtained CMB and SDSS data, we find that the recently derived data constraints favor the accelerated recombination model, although the other models (standard, delayed recombination) are not ruled out at 1\(\sigma\) confidence level. If the accelerated recombination had actually occurred in our early Universe, it is likely that baryonic clustering on small scales would have been the cause of it. By comparing the ionization history of baryonic cloud models with that of the best-fit accelerated recombination model, we find that some portion of our early Universe has baryonic underdensity. We have made a forecast for the PLANCK data constraint, which shows that we will be able to rule out the standard or delayed recombination models if the recombination in our early Universe had proceeded with \(\epsilon_\alpha \sim -0.01\) or lower, and residual foregrounds and systematic effects are negligible.

Keywords: CMBR polarization parameters, CMBR polarization theory, CMBR theory

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1. Introduction

The recombination process of cosmic plasma, which occurred around the redshift \(z_{\text{rec}} \approx 1100\), decouples photons from baryons \([1, 2]\). In the presence of Ly-\(\alpha\) photon sources, the recombination process might proceed with delay \([3–5]\), or with acceleration in the presence of baryonic clustering on small scales \([6–8]\). The cosmic microwave background (CMB) anisotropy, which is sensitive to the ionization history of our Universe, is affected by delay or acceleration of the recombination process \([3–7]\). The major effect on the CMB anisotropy is expected in the CMB polarization and small angular scale temperature anisotropy \([4–6, 8]\). The five-year data from the Wilkinson Microwave Anisotropy Probe (WMAP) \([9–11]\) is released and the recent ground-based CMB observations such as the ACBAR \([12,13]\) and QUaD \([14–16]\) provide information complementary to the WMAP data. In the near future, PLANCK Surveyor \([17]\) is going to measure the CMB temperature and polarization anisotropy with great accuracy over a wide range of angular scales. In this paper, we investigate the recombination models and baryonic cloud models, using the recently obtained CMB and SDSS data.

The outline of this paper is as follows. In section 2, we investigate the extended recombination models and show that the data constraints favor accelerated recombination models. In section 3, we discuss and constrain baryonic cloud models. In section 4, we make a forecast for the PLANCK data constraint. In section 5, we summarize our investigation with a conclusion.

2. Distortion on the standard ionization history

The presence of extra resonance photon sources may delay the recombination of cosmic plasma \([3–6]\), while the presence of baryonic clustering on small scales may accelerate the recombination \([6–8]\). The simplest model for the production of extra resonance photons \(n_{\alpha}\) is given by \([3,6]\)

\[
\frac{dn_{\alpha}}{dt} = \epsilon_{\alpha}(z) H(z) n,
\]

(1)
where \( n \) is the number density of atoms, \( H(z) \) is the Hubble expansion rate at a redshift \( z \), and \( \epsilon_\alpha(z) \) is a parameter dependent on the production mechanism. Since the thickness of the last scattering surface is very small in comparison to the horizon of the last scattering surface \( L_{ls} \), the dependence of \( \epsilon_\alpha(z) \) on \( z \) can be parameterized as \( \epsilon_\alpha(z_{rec}) + o(\Delta/L_{ls}) \). Hence, we use the approximation \( \epsilon_\alpha(z) \approx \epsilon_\alpha(z_{rec}) \) throughout our investigation. Though equation (1) was originally proposed for the delayed recombination, we use equation (1) to model the accelerated recombination by assigning negative values to \( \epsilon_\alpha \) [6]–[8]. However, it should be noted that the physical basis of the accelerated recombination (i.e. baryonic clustering on small scales) is different from that of the delayed recombination. We also would like to point out that the distortion of the CMB black body spectrum caused by the extended recombination process \( (0 < |\epsilon_\alpha| < 1) \) is negligible in comparison with the distortion caused by the reionization (see [18] for details), and is well within the COBE FIRAS data constraint [19].

By making a small modification to the RECFAST code [20]–[22], we have computed the ionization fraction \( x_e \) for various values of \( \epsilon_\alpha \) and plotted them in figure 1. We can see that the ionization fraction \( x_e \) of the recombination models \( \epsilon_\alpha < 0 \) drops much more quickly than that for the standard model \( \epsilon_\alpha = 0 \), while \( x_e \) for the recombination models \( \epsilon_\alpha > 0 \) drops much more slowly.

In figures 2–4, we show the temperature power spectra, \( E \) mode power spectra and \( TE \) correlation for various values of \( \epsilon_\alpha \). It is worth noting that the location and heights of the Doppler peaks are affected by the delay and acceleration of the recombination. As shown in figure 2, the accelerated recombination models \( (\epsilon_\alpha < -0.07) \) are not in good agreement with the WMAP data constraint (e.g. the first Doppler peak), and the delayed recombination models \( (\epsilon_\alpha > 0.3) \) are ruled out [4]. Hence we have investigated the recombination models \( (-0.07 \leq \epsilon_\alpha \leq 0.3) \). For data constraints, we have used the Sloan Digital Sky Survey (SDSS) data [23]–[25] and the recently obtained CMB observations (the WMAP five-year data [9, 10], the ACBAR 2008 [12, 13] and the QUaD [14]–[16]). Through
Figure 2. Temperature anisotropy power spectrum for $\epsilon_\alpha = -0.07, -0.03, 0, 0.1, 0.3$ in descending order of Doppler peak heights. The ACBAR 2008 and the binned WMAP five-year data are shown with error bars.

Figure 3. Temperature–$E$ mode correlation for $\epsilon_\alpha = -0.07, -0.03, 0, 0.1, 0.3$ in ascending order of trough heights. The WMAP five-year data and QUaD data are shown with error bars.

small modifications to the CosmoMC package [26], we have included the parameter $\epsilon_\alpha$ of the prior distribution $-0.07 \leq \epsilon_\alpha \leq 0.3$ in the cosmological parameter estimation and explored the multi-dimensional parameter space $(\Omega_b h^2, \Omega_c h^2, \tau, n_s, \log[10^{10} A_s], H_0, \epsilon_\alpha)$ by fitting the matter power spectra to the SDSS data, and the CMB anisotropy power spectra $C_l^{TT}$, $C_l^{TE}$ and $C_l^{EE}$ to the recent CMB observations (WMAP5YR + ACBAR + QUaD).

We have run the modified CosmoMC on an MPI cluster with six chains. For the convergence criterion, we have adopted the Gelman and Rubin ‘variance of chain means’ and set the R-1 statistic to 0.03 for the stopping criterion [27, 28]. The convergence, which is measured by the R-1 statistic, is 0.0262 and 15 107 chains steps are used.
Probing the last scattering surface through CMB observations

Figure 4. $E$ mode power spectrum for $\epsilon_\alpha = -0.07, -0.03, 0, 0.1, 0.3$ in descending order of Doppler peak heights. The QUaD data are shown with error bars.

Table 1. Cosmological parameters from $\Lambda$CDM + the extended recombination model constrained by WMAP5YR + ACBAR + QUaD + SDSS data.

| Parameter | 1σ constraint |
|-----------|----------------|
| $\Omega_b h^2$ | $0.0229^{+0.0017}_{-0.00017}$ |
| $\Omega_c h^2$ | $0.1066^{+0.0144}_{-0.0121}$ |
| $\tau$ | $0.0930^{+0.0348}_{-0.0448}$ |
| $n_s$ | $0.9625^{+0.0316}_{-0.0317}$ |
| $\log[10^{10} A_s]$ at $k_0 = 0.005$ Mpc$^{-1}$ | $3.0547^{+0.0912}_{-0.1075}$ |
| $H_0$ | $71.7303^{+9.4548}_{-8.2422}$ km s$^{-1}$ Mpc$^{-1}$ |
| $\epsilon_\alpha$ | $-0.0034^{+0.0185}_{-0.0237}$ |

In figure 5, we show the marginalized likelihood and mean likelihood of $\epsilon_\alpha$, given those observations. The solid lines and dotted lines correspond to the marginalized likelihood and the mean likelihood respectively (for the distinction between the marginalized likelihood and the mean likelihood, refer to [26]). Though we are aware that CosmoMC does not provide a precise best-fit value, we quote the best-fit value from CosmoMC as is often done in literature. Using the recent CMB + SDSS observation constraints, we find $\epsilon_\alpha = -0.00342^{+0.0185}_{-0.0237}$ at the 1σ confidence level and $\epsilon_\alpha = -0.00342^{+0.0214}_{-0.0305}$ at the 2σ confidence level. As also shown in figure 5, the current data constraints favor accelerated recombination models, though $\epsilon_\alpha \geq 0$ is still in the 1σ confidence interval. In figure 6, we have plotted the marginalized distribution and mean likelihoods in the plane of $\epsilon_\alpha$ versus $\{\Omega_b h^2, \Omega_c h^2, \tau, n_s, \log[10^{10} A_s], H_0\}$. We summarize 1σ constraints on cosmological parameters in table 1, given CMB + SDSS data. In comparison to the cosmological parameters estimated with the standard recombination model [11], the optical depth $\tau$ is affected most, while other cosmological parameters are affected negligibly.
Figure 5. CMB + SDSS: the marginalized likelihood (the solid curve) and the mean likelihood (the dashed curve). The normalization is chosen such that the peak value is equal to unity.

Figure 6. The marginalized likelihood in the plane of $\epsilon_\alpha$ versus six basic parameters, using the CMB + SDSS constraint. Two contour lines correspond to $1\sigma$ and $2\sigma$ levels.

3. Small scale baryonic cloud models and accelerated recombination

As discussed in [7], the presence of the baryonic clustering in the range of very small mass scales $M \sim 10^{-5}M_\odot$ can cause accelerated recombination. The simplest model for baryonic clustering is given by a baryonic cloud model [7] as follows:

$$\bar{\rho}_b = \rho_{b,\text{in}} f + \rho_{b,\text{out}} (1 - f),$$

(2)
where $\bar{\rho}_b$ is the mean density of baryonic matter, and $\rho_{b,\text{out}}$ and $\rho_{b,\text{in}}$ are the baryonic density of baryonic clouds and intercloud regions respectively, and $f$ is the total volume fraction of intercloud regions. Denoting the baryonic density contrast between the intercloud region and clouds by $\xi = \rho_{b,\text{in}}/\rho_{b,\text{out}}$, it may be easily shown that

$$\rho_{b,\text{in}} = \frac{\xi \bar{\rho}_b}{1 + f(\xi - 1)}; \quad \rho_{b,\text{out}} = \frac{\bar{\rho}_b}{1 + f(\xi - 1)}. \quad (3)$$

On the other hand, in the presence of baryonic clouds, there arises diffusion from clouds into intercloud regions, washing out density contrast. The characteristic scale of such diffusion is close to the Jeans length, $R_J \sim c_s\eta_t$, where $c_s$ is the baryonic speed of sound and $\eta_t = \int c \, dt/a(t)$ is the conformal time corresponding to the recombination time. Baryonic clouds of mass scales $M \sim 10^{-10} M_\odot$ have length scale $R_\alpha < R_J < R_\gamma$, where $R_\alpha$ and $R_\gamma$ are the mean free paths of resonance photons and CMB photons respectively. Hence we may neglect baryonic diffusion. The free electron density of clouds and intercloud regions, which we denote by $n_{e,\text{out}}$ and $n_{e,\text{in}}$ respectively, are given by

$$n_{e,\text{in}} = x_{e,\text{in}} \left(1 - \frac{1}{2} Y_p \right) \rho_{b,\text{in}}, \quad n_{e,\text{out}} = x_{e,\text{out}} \left(1 - \frac{1}{2} Y_p \right) \rho_{b,\text{out}}, \quad (4)$$

where $x_{e,\text{out}}$ and $x_{e,\text{in}}$ are the ionization fraction of clouds and intercloud regions, and $Y_p$ and $\rho_b$ are the mass fraction of $^4$He and the baryon number density respectively. The ionization fraction $x_e$ is given by $n_e/(n_e + n_p)$, where $n_p$ is the total number density of free protons and protons trapped in nucleus. Since scales of baryonic clouds are smaller than the mean free path of CMB photons, the effective ionization fraction, which CMB anisotropy is sensitive to, is given by the mean ionization fraction:

$$\langle x_e \rangle = \frac{\langle n_e \rangle}{\langle n_b \rangle} \left( 1 - \frac{Y_p}{2} \right), \quad (5)$$

where the mean value of free electron density is given by [7]

$$\langle n_e \rangle = n_{e,\text{in}} f + n_{e,\text{out}} (1 - f).$$

Using equations (2), (4) and (5), we may show that the effective ionization fraction has the following relation to the ionization fraction of clouds and intercloud regions:

$$\langle x_e \rangle = x_{e,\text{in}} G_{\text{in}} + x_{e,\text{out}} G_{\text{out}}, \quad (6)$$

where

$$G_{\text{in}} = \frac{\xi f}{1 + f(\xi - 1)} \left( 1 - \frac{Y_{p,\text{in}}}{2} \right), \quad (7)$$

$$G_{\text{out}} = \frac{1 - f}{1 + f(\xi - 1)} \left( 1 - \frac{Y_{p,\text{out}}}{2} \right), \quad (8)$$

We would like to give a reminder that the effective ionization fraction $\langle x_e \rangle$ is not necessarily equal to the ionization fraction of homogeneous baryonic model (i.e. $\xi = 1$), because the recombination process has non-linear dependence on the baryonic density.

As presented in section 2, the CMB data constraints with or without SDSS data favor the accelerated recombination models. Given certain values of $f$ and $\xi$, we can compute the ionization history (i.e. $x_e(z)$) of cloud and intercloud regions, using
Figure 7. Ionization history of the accelerated recombination model ($\epsilon_\alpha = -0.0034$) and the baryonic cloud model ($f = 0.019, \xi = 0.038$): the solid curve shows the ionization history of the accelerated recombination model and the dashed curve shows the ionization history of a baryonic cloud model. The two curves are visually identical.

Table 2. Best-fit baryonic cloud model.

| Constraints | $\epsilon_\alpha$ | $f$ | $\xi$ | $\rho_{b,\text{in}}/\bar{\rho}_b$ | $\rho_{b,\text{out}}/\bar{\rho}_b$ |
|-------------|-------------------|-----|-------|-------------------------------|----------------------------------|
| CMB + SDSS  | -0.0034           | 0.019 | 0.038 | 0.04                          | 1.02                             |

Provided that $\epsilon_\alpha = -0.0034$, we find that baryonic clouds with baryonic density $1.02\bar{\rho}_b$ occupy $\sim 98\%$ of the total volume in our early Universe, while intercloud regions with baryonic density $0.04\bar{\rho}_b$ occupy $\sim 2\%$. In table 2, we summarize the best-fit values of $f$, $\xi$, $\rho_{b,\text{in}}/\bar{\rho}_b$ and $\rho_{b,\text{out}}/\bar{\rho}_b$.

4. Forecast on the PLANCK data constraint

In this section, we forecast the PLANCK data constraint on $\epsilon_\alpha$. We have assumed FWHM = 10', $\Delta T/T = 2.5$ (Stokes I) and $\Delta T/T = 4$ (Stokes Q&U) [17, 30]. The pixel size is assumed to be equivalent to that of HEALPix [31, 32] pixelization with Nside = 1024.
Figure 8. Planck mock data ($\epsilon_\alpha = -0.01$): the marginalized likelihood (the solid curve) and the mean likelihood (the dashed curve). The normalization is chosen such that the peak value is equal to unity.

(Res 10). Assuming isotropic noise, we compute the noise power spectrum as follows:

$$N_l = N_0 \Delta \Omega e^{2\sigma^2}, \quad (9)$$

where $\sigma = \text{FWHM}/\sqrt{8\ln 2}$, $N_0$ is the noise variance per pixel and $\Delta \Omega$ is the solid angle of a single pixel [1].

We have obtained the forecast by feeding the PLANCK mock data and the SDSS data to the CosmoMC. The Planck mock data are generated by drawing spherical harmonic coefficients ($2 \leq l \leq 1500$) for the signal and noise respectively from Gaussian distributions, whose variances are equal to those of the CMB power spectra and equation (9) respectively. We have obtained the CMB power spectra by using CAMB [33] with the modified RECFAST and $\epsilon_\alpha = -0.01$. In the figure 8, we show the marginalized likelihood (the solid curve) and the mean likelihoods (the dashed curve) of $\epsilon_\alpha$, given the Planck mock data.

Given the mock data, CosmoMC finds $-0.015 < \epsilon_\alpha < -3.5 \times 10^{-6}$ and $-0.017 < \epsilon_\alpha < 0.0023$ at 1$\sigma$ and 2$\sigma$ level respectively, which is similar to the forecast of [5]. While the CosmoMC forecast in figure 8 is made with the mock data for $\epsilon_\alpha = -0.01$, we need to make forecast for $\epsilon_\alpha$ of various values. However, it is not practically feasible to run CosmoMC for various values of $\epsilon_\alpha$ because of the time usually required for running CosmoMC. Hence, we have estimated the 1$\sigma$ interval for various values of $\epsilon_\alpha$ via the Fisher matrix [1,34], which is given by [1,34]

$$F_{ij} = \left\langle -\frac{\partial^2 (\ln L)}{\partial \lambda_i \partial \lambda_j} \right\rangle \quad (10)$$

$$= \frac{1}{2} \text{Tr} \left[ \frac{\partial S}{\partial \lambda_i} (S + N)^{-1} \frac{\partial S}{\partial \lambda_j} (S + N)^{-1} \right], \quad (11)$$

where $\lambda_i$ denotes the parameters to be estimated. Evaluated at the maximum of the likelihood, the square root of the diagonal element of the inverse Fisher matrix yields the
marginalized 1σ error on the parameter estimation [1, 34]. The likelihood function for temperature and polarization anisotropy may be written as follows [35]:

\[
\mathcal{L} = \frac{1}{(2\pi)^{N/2}} |S + N|^{1/2} \exp\left[-\frac{1}{2}(S + N)^{-1}\Delta\right],
\]

where \(N\) is the number of data, \(\Delta\) is a data vector, \(S\) is a signal covariance matrix and \(N\) is a noise covariance matrix. We expand the anisotropy map in spherical harmonics so that our data vector \(\Delta\) consists of spherical harmonic coefficients \(a_{Tlm}\) and \(a_{Em}\). In general, the computation of equation (11) for a high resolution whole-sky observation such as the PLANCK observation is not possible on a modern computer at this moment. To facilitate the computation, we have made a few approximations. We assume very effective foreground cleaning with no need for sky masking and uniform instrument noise so that the signal and noise covariance matrices are block diagonal and do not depend on spherical harmonic index \(m\). In such configurations, the signal and noise covariance matrices are given by

\[
S = \text{diag}\left(\begin{pmatrix} C TT & C TE \\ C TE & C EE \end{pmatrix}, \ldots, \begin{pmatrix} C TT & C TE \\ C TE & C EE \end{pmatrix}, \ldots, \begin{pmatrix} C TT & C TE \\ C TE & C EE \end{pmatrix}\right),
\]

and

\[
N = \text{diag}\left(\begin{pmatrix} N_2 & 0 \\ 0 & N_2 \end{pmatrix}, \ldots, \begin{pmatrix} N_l & 0 \\ 0 & N_l \end{pmatrix}, \ldots, \begin{pmatrix} N_l & 0 \\ 0 & N_l \end{pmatrix}\right).
\]

Taking into account the repeating pattern of diagonal blocks, we may show

\[
\frac{1}{2} \text{Tr}\left[\frac{\partial S}{\partial \lambda_i} (S + N)^{-1} \frac{\partial S}{\partial \lambda_j} (S + N)^{-1}\right] = \frac{1}{2} \text{Tr}\left[\mathbf{L} \frac{\partial \tilde{S}}{\partial \lambda_i} (\tilde{S} + \tilde{N})^{-1} \frac{\partial \tilde{S}}{\partial \lambda_j} (\tilde{S} + \tilde{N})^{-1}\right],
\]

where

\[
\mathbf{L} = \text{diag}\left(\begin{pmatrix} 5 & 0 \\ 0 & 5 \end{pmatrix}, \ldots, \begin{pmatrix} 2l + 1 & 0 \\ 0 & 2l + 1 \end{pmatrix}\right),
\]

\[
\tilde{S} = \text{diag}\left(\begin{pmatrix} C TT & C TE \\ C TE & C EE \end{pmatrix}, \ldots, \begin{pmatrix} C TT & C TE \\ C TE & C EE \end{pmatrix}, \ldots, \begin{pmatrix} C TT & C TE \\ C TE & C EE \end{pmatrix}\right),
\]

\[
\tilde{N} = \text{diag}\left(\begin{pmatrix} N_2 & 0 \\ 0 & N_2 \end{pmatrix}, \ldots, \begin{pmatrix} N_l & 0 \\ 0 & N_l \end{pmatrix}, \ldots, \begin{pmatrix} N_l & 0 \\ 0 & N_l \end{pmatrix}\right).
\]

The right-hand side of equation (12) can be easily computed in a reasonable amount of time even for post-PLANCK whole-sky observations. We chose six basic parameters (\(\Omega_b h^2, \Omega_c h^2, h, A_s, n_s\)) plus \(\epsilon_\alpha\) for estimation parameters and set the values of the basic six parameters to the WMAP best-fit values [11, 35, 36]. Due to the non-linear dependence of the CMB power spectra on parameter \(\lambda_i\), we resorted to numerical differentiation to obtain \(\partial \tilde{S}/\partial \lambda_i\). The numerical derivatives are obtained by computing the following:

\[
\frac{C_l(\lambda_i + (1/2)\Delta \lambda_i) - C_l(\lambda_i - (1/2)\Delta \lambda_i)}{\Delta \lambda_i},
\]

\[l = 2, 3, \ldots, 2l + 1\].
where we have set $\Delta \lambda_i/\lambda_i = 10^{-3}$ for six parameters. For the given set of parameters $\lambda_i$, we have computed $C^{TT}_l$, $C^{TE}_l$, $C^{EE}_l$, using CAMB [33] with the modified RECFAST. While we have made the forecast for various $\epsilon_\alpha$ in the range of $-0.07 \leq \epsilon_\alpha \leq -0.3$, we find that equation (13) has numerical instability for $\Delta \epsilon_\alpha$ of very small values. Hence, we fixed $\Delta \epsilon_\alpha$ to be $-0.001$ instead of setting $\Delta \epsilon_\alpha/\epsilon_\alpha = 10^{-3}$.

The left plot in figure 9 shows the estimation error for $-0.07 \leq \epsilon_\alpha \leq 0.3$, while the right one shows the estimation error in the vicinity of $\epsilon_\alpha = 0$. Two solid lines denote the boundary of the $1\sigma$ confidence interval and the dashed line shows the central values of the $1\sigma$ interval, which are set to the true values of $\epsilon_\alpha$. We find that the $1\sigma$ error tends to increase with decreasing $\epsilon_\alpha$ and approaches $\sim 0.005$. We also find that the $1\sigma$ error forecast by the Fisher matrix method is smaller than the $1\sigma$ forecast from CosmoMC. The discrepancy between the CosmoMC forecast and the Fisher matrix forecast is attributed to the deviation of the parameter likelihood from a Gaussian distribution. While the Fisher matrix forecast is based on the marginalized likelihood with Gaussian approximation, the CosmoMC forecast estimates $1\sigma$ and $2\sigma$ intervals from the mean likelihood. However, we can learn from the Fisher matrix forecast that the $1\sigma$ errors for $-0.7 \leq \epsilon_\alpha \leq 0.3$ are of the same order of magnitude, which provides information complementary to the CosmoMC forecast. For the CosmoMC forecast as well as the Fisher matrix forecast, we have neglected residual foregrounds and systematic effects including the anisotropy of the instrument noise and beam asymmetry, which will be additional effective sources of noise. Hence, our forecast should be regarded as more of a lower limit on the estimation variance.

5. Discussion

We have investigated the extended recombination models, using the recently obtained CMB and SDSS data. We find that the data constraints favor accelerated recombination models, though other recombination models (standard, delayed recombination) are not

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3 For a Gaussian distribution, the marginalized likelihood and mean likelihood are identical.
Probing the last scattering surface through CMB observations

ruled out at the 1σ confidence level. By comparing the ionization history of baryonic cloud models with the best-fit accelerated recombination model, we have constrained the baryonic cloud models, from which we find that our early Universe might have slight overdensity of baryonic matter ∼1.02 ρb for ∼98% of the total volume and underdensity of baryonic matter ∼0.04 ρb for the rest of space. The origin of primordial baryonic clouds, if exists, might be associated with inhomogeneous baryogenesis [37] in our very early Universe.

While we have constrained baryonic cloud models indirectly by fitting the ionization history, a more accurate constraint will be obtained only when CMB power spectra of the baryonic cloud models are fitted directly to the data. Once we get enough evidence of accelerated recombination from the upcoming PLANCK data, we plan to constrain baryonic cloud models directly.

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Probing the last scattering surface through CMB observations

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