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Isocurvature fluctuations induce early star formation

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ABSTRACT

The early reionization of the Universe inferred from the *WMAP* polarization results, if confirmed, poses a problem for the hypothesis that scale-invariant adiabatic density fluctuations account for large-scale structure and galaxy formation. One can only generate the required amount of early star formation if extreme assumptions are made about the efficiency and nature of early reionization. We develop an alternative hypothesis that invokes an additional component of a non-scale-free isocurvature power spectrum together with the scale-free adiabatic power spectrum for inflation-motivated primordial density fluctuations. Such a component is constrained by the Lyman alpha forest observations, can account for the small-scale power required by spectroscopic gravitational lensing, and yields a source of early star formation that can reionize the Universe at $z \sim 20$ yet becomes an inefficient source of ionizing photons by $z \sim 10$, thereby allowing the conventional adiabatic fluctuation component to reproduce the late thermal history of the intergalactic medium.

Key words: stars: formation – galaxies: formation – intergalactic medium – cosmology: theory – early Universe – large-scale structure of Universe

1 INTRODUCTION

There have been major recent advances in cosmology with impact on galaxy formation theory. These include the detection of the temperature–polarization cross power spectrum for the CMB by *WMAP* (Kogut et al. 2003), and measurements both of the CMB temperature power spectrum and the underlying matter power spectrum with unprecedented accuracy, utilizing the *WMAP*, 2DF and quasar Lyα absorption line data sets (Bennett et al. 2003; Spergel et al. 2003). Two results that have received considerable attention are the optical depth of the Universe $\tau = 0.17 \pm 0.03$, which requires that the epoch of reionization occurs at $z = 15$–20 from *WMAP* (Kogut et al. 2003; Spergel et al. 2003), and the rolling spectral index $\mathrm{d}n/\mathrm{d}\ln k = -0.03 \pm 0.01$ for approximately scale-invariant density fluctuations for a combination of *WMAP*, 2DF and Lyα data (Spergel et al. 2003).

There is some tension between these results: if both are correct, it is difficult to understand how recombination occurred so early without some modification of the canonical model of primordial, nearly scale-invariant Gaussian adiabatic density fluctuations (Ciardi, Ferrara & White 2003; Fukugita & Kawasaki 2003; Haiman & Holder 2003; Somerville, Bullock & Livio 2003). In fact, a new Lyα absorption data set from the SDSS quasars has independently found evidence for a rolling spectral index (Seljak 2003), although an independent analysis of the same data does not reproduce sufficiently small error bars to confirm this result (Abazajian & Dodelson 2003).

The Lyα lines measure power in the underlying matter power spectrum on a comoving scale of around 1 Mpc. The results are however subject to bias, since one has to be confident that the gas is relatively unperturbed by feedback, such as is seen in the vicinity of Lyman break galaxies to Mpc distances. Hence it is of particular interest to consider another measure of the power spectrum on even smaller comoving scales, 10^{-2} to 0.1 Mpc. This comes from spectroscopic gravitational lensing of the quasar emission line region on several scales, the magnification ratios requiring and constraining substructure in the massive lensing haloes (Metcalf et al. 2004). One needs substantial power in objects of 10^6 to 10^9 $\mathrm{M}_\odot$, amounting to between 4 and 7 per cent of the galaxy surface density, and this cannot easily be accommodated in the usual CDM models with standard elliptical isothermal lens mass profiles. Previous estimates of halo substructure from gravitational lensing using simple lens models are highly uncertain (Dalal & Kochanek 2002). Moreover the numerical simulations of haloes suggest that, for nearly scale-invariant initial conditions, small-scale power may largely be erased in the inner haloes. One is in a dangerous regime of the spectrum where $n_{\mathrm{eff}} \approx -3$, and tidal destruction is effective. Indeed it is not clear whether the simulations have enough resolution adequately to address the question of the survival of small-scale substructure.

We propose an alternative prescription for small-scale power that satisfies all observed constraints and unambiguously predicts the

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survival of small-scale power, with some inflationary motivation. We postulate that, as is common to multifield inflationary models, both isocurvature and adiabatic fluctuation modes are generated (see, for example, Peebles 1999). A recent model motivated by inflation is a so-called curvaton model (Moroi & Takahashi 2001; Enqvist & Sloth 2002; Lyth & Wands 2002) in which an additional scalar field besides the inflaton – the curvaton – produces fluctuations during the reheating epoch. If the isocurvature fluctuations were generated by inflaton and curvaton generated adiabatic modes, there may be a possibility of having a non-scale-free isocurvature power spectrum together with the $n = 1$ scale-free adiabatic power spectrum (Moroi, private communication). As well as this curvaton hypothesis, a sub-dominant contribution of cosmic strings induced by brane inflation in superstring theory (Jones, Stoica & Tye 2003) may provide additional small-scale power.

The isocurvature contribution is described by two parameters: the amplitude normalization and the spectral index. Without specifying a model, unfortunately, we do not really know the differences of the power-law indices for the adiabatic and isocurvature components. We recall that the usual definition of the spectral index n of the isocurvature mode, which is defined by the entropy perturbations $S(k)$ as $\langle|S(k)|^2\rangle \propto k^n$, differs from that of the adiabatic mode, defined by density perturbations as $\langle|\delta(k)|^2\rangle \propto k^{n_{\rm adi}}$. From these definitions, $n = -3$ corresponds to the scale-invariant power spectrum while $n_{\rm adi} = 1$ for the adiabatic mode.

We take these two parameters, i.e. the amplitude normalization and the spectral index, to be freely assignable, but chosen to give more small-scale power than the rolling or nearly scale-invariant index adiabatic fluctuations measured on larger scales. We use Lyα forest data to constrain these parameters. The amount of excess small-scale power can be tuned by adjusting the spectral index within the allowed constraints. We normalize at 1 Mpc, the central point of the Lyα probes. Small-scale power survives because the fluctuations become nonlinear earlier than in the pure adiabatic case, owing to the isocurvature component boost. The first nonlinear fluctuations form earlier and hence lead to denser substructures that are resistant to tidal disruption within massive haloes.

The two-component model has two advantages. It results in early star formation, regardless of the spectral index measured for the adiabatic component on large scales. Hence early reionization can be achieved. It also preserves small-scale power as hierarchical clustering develops, in the form of dense 10^6-M$_\odot$ clumps in massive dark haloes. This helps to explain quadruple quasar lensing flux ratios as well as the bending of radio minijets. A related discussion was given in Afshordi, McDonald & Spergel (2003), who considered an isocurvature component as a source of primordial black hole formation.

In the remainder of this paper, we give constraints from the Lyα forest on the isocurvature component and we discuss the observational implications. We give several applications: in addition to the implications for the epoch of reionization and halo microlensing, we discuss the possible implications for patchy reionization and SZ signatures of very early star formation via baryon trapping in dense early substructures, and the clustering of early forming substructures and implications for the formation of the first stars.

2 MODELS

In this section, we estimate the isocurvature contributions in the power spectrum based on observations of the Lyα forest. As we mentioned in the previous section, we may expect to have dominant isocurvature fluctuation modes on small scales ($\sim$ kpc), which induce early reionization, from multifield inflationary models, i.e. a curvaton model or cosmic strings of brane inflation.

From *WMAP* results, it is known that the nature of fluctuations is consistent with the adiabatic mode and the contribution of isocurvature perturbations cannot be dominant on the relevant measurement scales, which are $k \lesssim 0.05$ Mpc^{-1} (Bennett et al. 2003; Spergel et al. 2003).

On smaller scales, $k \sim 1$ Mpc^{-1}, the amplitude of isocurvature fluctuations is constrained by the Lyα forest (Croft et al. 1998; Nusser & Haehnelt 1999). The joint analysis of *WMAP*, 2DF and Lyα shows the power spectrum obtained by Lyα is significantly lower than that extrapolated from a single power-law ΛCDM model consistent with *WMAP* data alone (Spergel et al. 2003).

Several new analyses of the Lyα power spectrum based on the Sloan Digital Sky Survey data are becoming available (Abazajian & Dodelson 2003; Seljak 2003). Although they employed the same data sets, each group has obtained different values. Among them, Seljak (2003) provides the lowest amplitude of the power spectrum and the smallest error bars. Therefore here we take his value as a reference. We set the normalization of the isocurvature fluctuations to be 10 per cent of Seljak's power spectrum. We should notice that this is merely an upper limit on the possible isocurvature contributions.

On the other hand, Abazajian & Dodelson (2003) give a relatively high central value with larger error bars. The central value of their power spectrum indeed exceeds the extrapolation from the *WMAP* power-law ΛCDM power spectrum. Here we have one extreme model assuming that the difference between the Abazajian & Dodelson power spectrum and the *WMAP* power-law spectrum is due to the existence of the isocurvature contributions. Then we immediately obtain the amplitude and the power-law index (which is $n = -1.7$) of the isocurvature power spectrum. The corresponding power spectra are shown in Fig. 1.

3 REIONIZATION

We estimate the number of photons emitted from Population III stars, which is a crucial element for the reionization process, following Somerville & Livio (2003) and Somerville et al. (2003).

First, employing the Press–Schechter prescription, we calculate the fraction of the total mass in collapsed haloes $F_{\rm h}$ with masses greater than $M_{\rm crit}$ and lower than $M_{\rm vir}$. Here we adopt $M_{\rm crit} = 1 \times 10^6\ h^{-1}$ M$_\odot$ and $M_{\rm vir} = M(T_{\rm vir} = 10^4$ K). Objects whose virial temperature is larger than 10^4 K can cool via atomic hydrogen and we assume them to be Population II stars.

From $F_{\rm h}$, we can calculate the global star-formation-rate density as

$$\dot{\rho_*} = e_* \rho_{\rm B} \frac{{\rm d}F_{\rm h}}{{\rm d}t}\,(M_{\rm vir} > M > M_{\rm crit})\,, \tag{1}$$

where e_* is the star-formation efficiency, which we take to be 0.002 for Population III stars with 200 M$_\odot$ and 0.001 with 100 M$_\odot$, and $\rho_{\rm B}$ is the comoving background baryon density (Yoshida et al. 2003a).

Let us assume Population III stars produce ${\rm d}N_\gamma/{\rm d}t = 1.6 \times 10^{48}$ photons s^{-1} M$_\odot^{-1}$ for a lifetime $\Delta t = 3 \times 10^6$ yr (Bromm et al. 2001). Therefore we can write ${\rm d}N_\gamma/{\rm d}t = N_{\gamma,0}\Theta(t)$, where $N_{\gamma,0} = 1.6 \times 10^{48}$ photons s^{-1} M$_\odot^{-1}$ and $\Theta(t)$ is a step function such that $\Theta(t) = 1$ for $t < \Delta t$ and $\Theta(t) = 0$ for $t > \Delta t$. Using this expression, the total production rate of ionizing photons per cubic Mpc at time

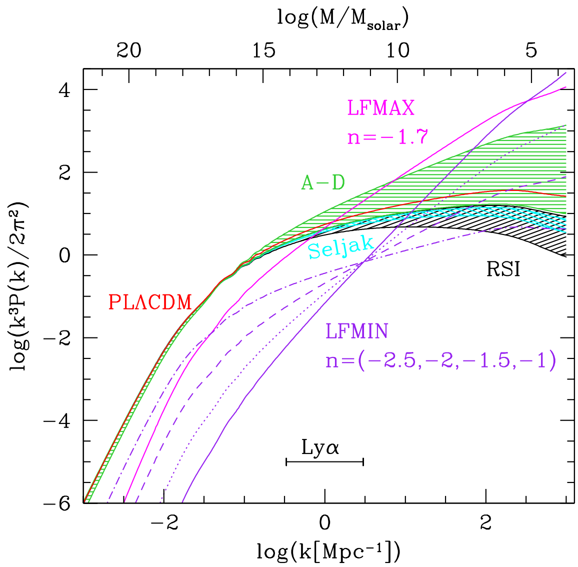

Figure 1. The matter power spectra. The red line (thick line with the label PLΛCDM) is the *WMAP* best fitted power-law ΛCDM model (PLΛCDM) (Spergel et al. 2003), the black hatched region is the running spectral index (RSI) model with errors fitted by *WMAP*, 2DF and Lyα (Spergel et al. 2003), and the blue (thick) and green (thin, horizontal) hatched regions are the RSI model with the SDSS Lyα power spectrum analysed by Seljak (2003) and Abazajian & Dodelson (2003), respectively. Purple lines (dot–dashed, dashed, dotted and solid lines, from left to right), which are labelled as LFMIN (Lyα Forest Minimum), are isocurvature power spectra with $n = -2.5, -2, -1.5$ and -1 normalized to 10 per cent of Seljak's Lyα analysis. The pink (grey solid) line labelled as LFMAX (Lyα Forest Maximum) is the isocurvature power spectrum by assuming the excess of the central value of Abazajian & Dodelson (2003) is caused by isocurvature contributions.

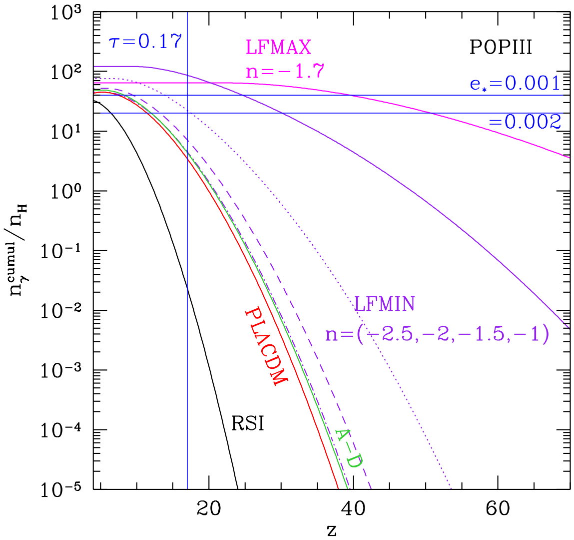

Figure 2. Cumulative photons emitted from Population III stars. Models are the same as in Fig. 1 while here we take the central value for the running spectral index model (RSI) from the Abazajian & Dodelson SDSS analysis (A-D). The difference between power-law ΛCDM (PLΛCDM) and A-D is very small. We take $e_* = 0.002$, the star-formation efficiency, to calculate the *y*-axis. Assuming 20 photons per hydrogen atom is needed to reionize the IGM, we draw a straight horizontal line at 20 with the label $(e_*) = 0.002$. The intersection of each curve with this line provides the reionization epoch. We can simply renormalize the value of the *y*-axis for different values of e_*. If we assume $e_* = 0.001$, for example, 20 photons per hydrogen atom corresponds to 40 photons in this figure. Accordingly, the horizontal line to provide the reionization epoch shifts upwards as is shown with the label $e_* = 0.001$.

t' becomes

$$\frac{dn_\gamma}{dt}(t') = \int_0^{t'} \frac{dN_\gamma}{dt}(t'-t)\dot{\rho}_*(t)\,dt$$
$$= e_*\rho_B N_{\gamma,0}\int_0^{t'} \Theta(t'-t)\frac{dF_h}{dt}(t)\,dt$$
$$= e_*\rho_B N_{\gamma,0}\int_{t'-\Delta t}^{t'} \frac{dF_h}{dt}(t)\,dt$$
$$= e_*\rho_B N_{\gamma,0}\left[F_h(t') - F_h(t'-\Delta t)\right]. \quad (2)$$

Then we can obtain the cumulative number of photons per H atom as

$$\frac{n_\gamma^{\rm cumul}}{n_H}(t_0) = \frac{\mu m_p}{\rho_B}\int_0^{t_0}\frac{dn_\gamma}{dt}(t')\,dt'$$
$$= \mu m_p e_* N_{\gamma,0}\int_0^{t_0}[F_h(t') - F_h(t'-\Delta t)]\,dt', \quad (3)$$

where n_H is the Hydrogen number density and *mp* is the proton mass. Here we may employ the approximation $F_h(t') - F_h(t'-\Delta t) \simeq dF_h/dt'(t')\Delta t$, and we obtain $n_\gamma^{\rm cumul}/n_H(t_0) \simeq \mu m_p e_* N_{\gamma,0} F_h(t_0)\Delta t$. We checked this approximation works almost perfectly well for $z < 40$ when the Hubble time is longer than Δt.

For calculating the number of photons emitted from Population II stars, we replace $M_{\rm vir} > M > M_{\rm crit}$ of equation (1) with $M > M_{\rm vir}$ and set $e_* = 0.1$ and $dN_\gamma/dt = 8.9 \times 10^{46}$ photons s^{-1} $M_\odot^{-1}$ for a lifetime of $\Delta t = 3 \times 10^6$ yr (Somerville & Livio 2003).

4 RESULTS

In Fig. 2, the cumulative number of photons emitted from Population III stars per hydrogen atom as a function of redshift is shown for the power-law ΛCDM model with *WMAP* parameters, the running spectrum index model, isocurvature models with the power-law index $n = -2.5, -2, -1, -1.5, -1$, whose amplitudes are set as 10 per cent of Seljak's analysis of the Lyα forest, the isocurvature model with $n = -1.7$, which explains the excess of the power spectrum obtained by the analysis of Lyα clouds by Abazajian & Dodelson against the power-law ΛCDM and the model fitted by Abazajian & Dodelson. Here, we take $e_* = 0.002$. However, we can simply renormalize the value of the *y*-axis for different values of e_*.

In Fig. 3, the cumulative number of photons emitted from Population II stars per hydrogen atom as a function of redshift is shown. It is clear from Figs 2 and 3 that contributions from Population II stars to early reionization are almost negligible, while the Universe can be reionized by only Population II stars in our most extreme case, i.e. LFMAX.

To get the ionization fraction, we have to multiply $f_{\rm esc} f_{\rm ion}/C_{\rm clump}$ where $f_{\rm esc}$ is the escape fraction of photons from the galaxy, $f_{\rm ion}$ is the number of ionizations per UV photon, and $C_{\rm clump}$ is the clumping factor of IGM, respectively. It is known that about 5 to 20 photons per H atom are required to achieve a volume-weighted ionization fraction of 99 per cent (Haiman, Abel & Madau 2001; Sokasian et al. 2003a,b). We take 20 as our reference. In Fig. 2, this number is plotted as the horizontal line. If we assume $e_* = 0.001$ instead 0.002, 20 photons per H atom correspond to 40 photons in this figure, which we also plotted as a horizontal line. The crossing of each line with this horizontal line gives the epoch of reionization.

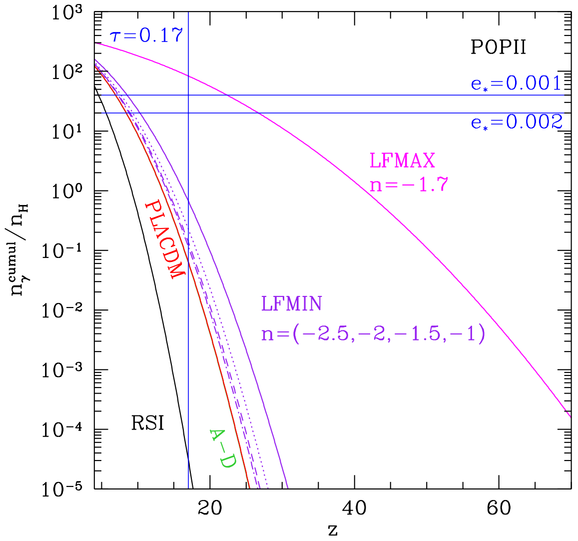

Figure 3. Cumulative photons emitted from Population II stars. Models are the same as in Fig. 2.

Table 1. Redshifts at which the cumulative number of photons becomes 10, 20 and 40. Redshifts when the cumulative number of photons from Population II becomes equal to that from Population III are also shown.

Model	n_γ^{cumul}/n_H 10	20	40	Population II = Population III
RSI	8.7	7.3	5.9	5.2
PLΛCDM	14	12	9.6	6.8
A-D	15	12	10	6.6
iso $n = -2.5$	15	13	10	7.1
iso $n = -2$	16	14	11	6.8
iso $n = -1.5$	21	18	14	6.0
iso $n = -1$	35	30	25	5.6
iso $n = -1.7$ (A-D)	59	51	40	19

The vertical line in this figure is $z = 17$, which is the reionization epoch for *WMAP* with instantaneous reionization.

In Table 1, we summarize the 'reionization' epoch of each model. These numbers correspond to $e_* = 0.002$. If we employ $e_* = 0.001$ and assume the cumulative number of photons needed for reionization is between 10 and 40 per H atom, the corresponding redshifts at which this occurs are given in this table. It is clear that the running spectrum index model cannot plausibly have early enough reionization and that the power-law ΛCDM is marginally consistent with *WMAP* results. These results are consistent with previous work (Ciardi et al. 2003; Fukugita & Kawasaki 2003; Haiman & Holder 2003; Somerville & Livio 2003; Yoshida et al. 2003b). It should be noticed that these redshifts for models with isocurvature fluctuations besides the A-D model are upper limits since we choose the amplitudes of power spectra to be as large as possible without violating Lyα constraints.

5 DISCUSSION

We have argued that an additional component of a non-scale-free isocurvature power spectrum together with the scale-free adiabatic power spectrum for inflation-motivated primordial density fluctuations allows us the freedom to generate the required amount of early star formation that gives early reionization. The power spectrum in our model has been normalized to the Lyman alpha forest observations. The late thermal history of the intergalactic medium is unchanged.

We may also account for a second epoch of reionization. One interesting aspect is that the number of cumulative photons per H atom by Population III stars asymptotes to constant at a later epoch for some models. See the LFMIN models of Fig. 2, for example. In the case of $n = -1$, we can clearly see the flattening in the number of photons at $z \gtrsim 7$. We speculate that this flattening may allow the small neutral H fraction observed in the spectra of the highest redshift SDSS QSOs via the Gunn–Peterson effect. We recall that the predicted number of photons of these LFMIN models are upper limits. We can renormalize the number of ionizing photons to be around 20 per H atom at $z = 17$ by assuming a 2 per cent amplitude relative to Seljak's Lyα power spectrum, and 10 photons per H atom for 1 per cent if $n = -1$. These models with $n \geqslant -1.5$ can provide enough energetic photons to reionize the Universe early enough to give $\tau = 0.17$.

6 APPLICATIONS

We expect there to be additional observational probes for the introduction of the isocurvature mode at small scales owing to an excess in the number of small objects. Among them, we speculate below on the microlensing effect induced by small haloes, the abundance of minihaloes, and baryon trapping in the substructure. We think it of interest to give a qualitative discussion of these effects, preferring not to go into excessive detail given the uncertainties inherent in our basic model.

6.1 Halo microlensing

The flux ratios of several quadruple-lensed quasars can only be interpreted if halo substructure is adding differentially to the lensing optical depth. Between 0.6 and 7 per cent of the halo mass is required to be in structures of mass up to 10^8–10^{10} $M_\odot$, within a projected radius of 10kpc of a massive halo at $z = 0.6$ (Dalal & Kochanek 2002; Metcalf et al. 2004). Most of the contribution to the optical depth comes from within the scale radius of the dark halo, since at larger radii the mean halo density decreases as r^{-3}. However, the numerical simulations do not have the resolution to tell whether the halo substructure survives, for a canonical scale-invariant initial spectrum of fluctuations. Semi-analytical methods suggest that the substructure fraction is insensitive to tilt or roll, but possibly too low (Zentner & Bullock 2003) for the purely adiabatic model.

The model advocated here may be able to accommodate the needs of halo substructure lensing, as the early forming substructures are more numerous and denser, and so resistant to tidal disruption. More work needs to be done on this issue.

6.2 The mass fraction in minihaloes, Populations II and III at high z

We may define minihaloes to be dark matter clouds which are below the mass threshold for star formation. The relevant mass range for minihaloes that can trap baryons requires temperatures above that of the CMB and masses above about $10^4\ h^{-1}$ $M_\odot$. In contrast, cooling is only effective at masses above approximately 10^6 $M_\odot$.

The abundance of minihaloes is shown in Fig. 4 as a function of redshift in a typical isocurvature/adiabatic model. Note that they are

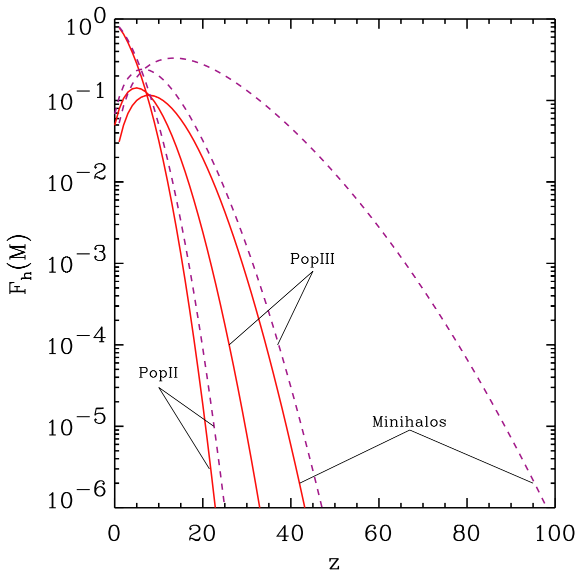

Figure 4. The mass fraction of haloes, within a given mass range, is shown as a function of redshift for the PLΛCDM model (solid lines) and the $n = -1.5$ isocurvature reionization model (dashed lines). For each model, three cases are presented: mass intervals defined by all masses with $T_{\rm vir} > 10^4$ K (predominantly haloes that cool via Lyα and form Population II stars); masses with $T_{\rm vir} < 10^4$ K and above $10^6\ h^{-1}$ M$_\odot$ (predominantly haloes that cool via H_2 and form Population III stars); and minihaloes of mass above $10^4\ h^{-1}$ M$_\odot$ and less than $10^6\ h^{-1}$ M$_\odot$ (haloes that are too low in mass to cool) but may contain residual trapped gas.

more numerous out to $z \sim 40$ than the peak in the ΛCDM model, which occurs for minihaloes at $z \sim 10$.

Also shown in Fig. 4 are the mass fractions in Population III and in Population II stars that form in dwarf galaxy haloes. These are defined by the respective criteria that H_2 and Lyα cooling are the dominant dissipative mechanisms for concentrating the baryons and enabling fragmentation to proceed. We base our criteria for formation of Population III and Population II stars in primordial clouds on the formulation by Haiman & Holder (2003) in terms of Type II versus Type I haloes. Their classification is based on the distinction between H_2 and H I cooling: we simply take this definition to its logical conclusion, given that the consensus view is that molecular cooling results in very massive stars (Population III) and atomic cooling allows fragmentation to the 'normal' mass range (Bromm, Kudritzki & Loeb 2001; Abel, Bryan & Norman 2002; Omukai & Yoshi 2003). The corresponding mass ranges are defined by all masses with $T_{\rm vir} < 10^4$ K and above $10^6\ h^{-1}$ M$_\odot$ (predominantly haloes that cool via H_2 and form Population III stars), and by all masses with $T_{\rm vir} > 10^4$ K (predominantly haloes that cool via Lyα and form Population II stars).

We see that Population III stars are boosted by an order of magnitude at $z \sim 20$, although Population II star formation is not greatly affected by the isocurvature admixture relative to ΛCDM. This is because the mass fraction in the relatively massive clouds required in this latter case, typically in excess of $\sim 10^9\ h^{-1}$ M$_\odot$, is strongly constrained by our model, which incorporates the requirement that we cannot overly perturb the Lyα forest.

6.3 Baryon trapping and SZ fluctuations

We finally speculate on some observable consequences that may distinguish our model from a purely adiabatic model. Consider the effects of baryon trapping in the isocurvature perturbation-induced substructure. This will have the effect of enhancing the temperature and SZ fluctuations produced at reionization relative to those predicted for the pure adiabatic case. Even if the baryons cannot cool, they are trapped at high redshift in dark matter minihaloes of mass above about $10^4\ h^{-1}$ M$_\odot$. The baryon overdensity is $\sim(\sigma_v/v_s)^2$, where σ_v is the velocity dispersion in the dark matter minihalo and v_s is the gas sound velocity. Trapping occurs only if $T > T_{\rm CMB}$, and this happens in the more massive minihaloes, for example, above $10^4\ h^{-1}$ M$_\odot$. Cooling via H_2 further enhances the gas density in late-forming minihaloes. This may imprint fine-scale structure on the CMB sky at reionization.

Some minihaloes could retain gas supported in a stable configuration by dark matter self-gravity (Umemura & Ikeuchi 1986; Gerhard & Silk 1996) and be abundant before reionization. This could provide a unique window on the dark ages of the early Universe via radio and NIR observations of a diffuse background of redshifted 21-m and Lyα emission. For example, with 100 Lyα photons per baryon, one might see at 2μ a 1 per cent contribution to the diffuse extragalactic background, which amounts to $\nu i_\nu \approx 10$ nw m^{-2} sr^{-1}, but could however be spectrally concentrated in a feature with width $\Delta\nu/\nu \sim 0.1$ associated with the epoch of reionization.

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