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CONSTRAINTS ON THE COSMIC STRUCTURE FORMATION MODELS FROM EARLY FORMATION OF GIANT GALAXIES

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ABSTRACT

A recent observation of Steidel and coworkers indicates that a substantial fraction of giant galaxies were formed at an epoch as early as redshift $z > 3$–3.5. We show that this early formation gives strong constraints on models of cosmic structure formation. Adopting the *COBE* normalization for the density perturbation spectrum, we argue that the following models do not have large enough power on galactic scales to yield the observed abundance: (1) standard cold dark matter (CDM) models (where mass density $\Omega_0 = 1$ and power index $n = 1$) with the Hubble constant $h \lesssim 0.35$; (2) tilted CDM models with $h = 0.5$ and $n \lesssim 0.75$; (3) open CDM models with $h \lesssim 0.8$ and $\Omega_0 \lesssim 0.3$; and (4) mixed dark matter models with $h = 0.5$ and $\Omega_\nu \gtrsim 0.2$. Flat CDM models with a cosmological constant $\lambda_0 \sim 0.7$ are consistent with the observation, provided that $h \gtrsim 0.6$. Combined with constraints from large-scale structure formation, these results imply that the flat CDM model with a low Ω_0 is the one fully consistent with observations. We predict that these high-redshift galaxies are more strongly clustered today than normal galaxies.

Subject headings: cosmology: theory — dark matter — galaxies: formation

1. INTRODUCTION

Recently Steidel and collaborators (Steidel et al. 1996, hereafter S96) have developed a novel photometric technique to detect high-redshift galaxies using the Lyman continuum break. They have found a number of candidate galaxies with redshift $z = 3$–3.5 in broadband photometry, and their follow-up spectroscopy has confirmed that these galaxies indeed have, or are consistent with having, such redshift. About 2% of the galaxies in the magnitude range $R_{\rm AB} = 23.5$–25 mag have $z = 3$–3.5. They have also argued from the equivalent widths of saturated absorption lines that the velocity dispersion of these galaxies is probably as high as 180–320 km s^{-1}, comparable to that for $L > L^*$ elliptical galaxies observed today, although the possibility is not excluded that the equivalent widths are dominated by P Cygni profile of gas outflows. These observations indicate that a substantial fraction ($\gtrsim$10%–30%) of giant galaxies observed today have already formed before this redshift. The observed spectra and colors of these "Lyman break galaxies" suggest that the formation epoch could probably be earlier by $\Delta t \simeq 1$ Gyr. While we have to await the confirmation with high-resolution spectroscopy as to whether the observed velocity dispersion is dominantly gravitational, it is very likely that they are beginning to observe an early stage of spheroids of giant galaxies.

We note that this abundance information of high-z galaxies gives strong constraints on models of cosmic structure formation. The current structure formation models, which are tuned to reproduce the observed large-scale structure at $z \approx 0$ and thus difficult to discriminate by observations at low z, lead to quite different predictions for small-scale structure at an early epoch, such as high-z galaxies. We argue that even the current rather premature data on high-z galaxies can discriminate models, if the normalization of the primordial spectrum is given. We also discuss the clustering properties of these galaxies.

2. MODELS

We take as a basis of our argument the Press-Schechter formalism (Press & Schechter 1974), which allows an analytic treatment of the problem. This formalism has been tested extensively by N-body simulations for a variety of hierarchical clustering processes in various cosmogonies (e.g., Bond et al. 1991; Bower 1991; Lacey & Cole 1994; Mo & White 1996; Mo, Jing, & White 1996). The comoving number density of dark halos in a unit interval of halo velocity dispersion σ is given by

$$\frac{dN}{d\sigma}(\sigma, z) = \frac{-3}{(2\pi)^{3/2}} \frac{1}{r_0^3\,\sigma} \frac{\delta_c(z)}{\Delta(r_0)} \frac{d\ln\Delta(r_0)}{d\ln r_0} \times \left(\frac{d\ln\sigma}{d\ln r_0}\right)^{-1} \exp\left[-\frac{\delta_c^2(z)}{2\Delta^2(r_0)}\right], \quad (1)$$

where r_0 is the radius of a sphere that comprises a halo of mass M for a homogeneous universe with mean mass density ρ_0, i.e., $M = 4\pi\rho_0 r_0^3/3$; $\Delta(r_0)$ is the rms of the linear mass density fluctuations in top-hat windows of radius r_0; $\delta_c(z)$ is the critical overdensity for collapse at redshift z. The quantity $\Delta(r_0)$ is completely determined by the linear power spectrum $P(k)$ (which is assumed to be Gaussian), and we normalize $P(k)$ by specifying $\sigma_8 \equiv \Delta(8h^{-1}$ Mpc), where h is the Hubble constant H_0 in units of 100 km s^{-1} Mpc^{-1}. For any given cosmological model and $P(k)$, one can calculate $dN/d\sigma$ given the function $\delta_c(z)$ and the relationship between σ and r_0. We take the result summarized by Kochanek (1995) for these relations.

We consider five sets of cosmic structure formation models, each containing one free parameter for which a constraint is to be derived. The first four sets are cold dark matter (CDM) models, which are described by Ω_0 (the cosmic mass density), $\lambda_0 \equiv \Lambda/3H_0^2$ (the cosmic density of cosmological constant), n (the power index of primordial density perturbation spec-

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TABLE 1

MODEL PARAMETERS

Model	h	n	Ω_0	λ_0	Ω_ν
Standard CDM	varying	1.0	1.0	0.0	0.0
Tilted CDM	0.5	varying	1.0	0.0	0.0
Open CDM...........	0.5–0.8	1.0	varying	0.0	0.0
Flat CDM	0.5–0.8	1.0	$1-\lambda_0$	varying	0.0
MDM.................	0.5	1.0	1.0	0.0	varying

trum), and h. In the fifth set, we discuss mixed dark matter (MDM) models with varying neutrino mass density Ω_ν. The model parameters are summarized in Table 1. For CDM models, the power spectra are calculated using the fitting formulae of Hu & Sugiyama (1996). We take the baryon density $\Omega_b = 0.0125\,h^{-2}$ (Walker et al. 1991). The amplitudes of $P(k)$ are estimated from the four year *COBE* data (Bennett et al. 1996) with the aid of the fitting formulae given by White & Scott (1996). The contribution of the gravitational wave to the normalization is ignored. For MDM models, we use the fitting formulae of Ma (1996) to estimate both $P(k)$ and *COBE* normalization.

In the calculation of the comoving number density of halos in equation (1), we need to specify the velocity dispersion of galactic halos and the epoch when they formed. We take the threshold velocity dispersion to be $\sigma_{\rm min} = 180$ km s^{-1}, accepting the S96 interpretation that the line width is gravitational. The true halo velocity dispersion could be higher than that of stars, as discussed by Gott (1977). We evaluate the comoving number density of galaxies for two epochs: (1) 1 Gyr before the epoch that corresponds to $z = 3$, and (2) at $z = 3.5$. Case (1) is probably more realistic for these galaxies, as inferred from the $R - G$ color assuming that some star formation activity persists to $z = 3$. Case (2) is true only when star burst is instantaneous: a strong rest frame UV light implies that the burst epoch is only 0.01 Gyr back from the observed epoch. As noted by S96, this is an unlikely case, since it requires all observed galaxies to undergo a completely coeval burst phase at the observed redshifts. We take case (2) as the most conservative estimate.

3. RESULTS

The abundance estimate of Lyman break galaxies depends on the assumed cosmology. S96 estimated that the comoving number density is $N_g \approx 2.9 \times 10^{-3}\ h^3$ Mpc^{-3} in the Einstein–de Sitter universe and $5.4 \times 10^{-4}\ h^3$ Mpc^{-3} in an open universe with $\Omega_0 = 0.1$. For other cosmologies, it is straightforward to estimate the density by modifying the comoving volume in the redshift range $3.0 \leq z \leq 3.5$ into the one for the relevant case.

We should note that what is calculated with equation (1) is halo abundance, and that some halos may not contain "galaxies" if star formation is for some reasons inhibited in them at the relevant epoch. Taking into account this fact and the fact that the velocity dispersion of a halo could be higher than is observed for stars (see § 2), we take the N_g given by S96 as a lower limit to the halo number density. It could also be possible that some massive halos contain more than one galaxy, and the actual number density of halos is smaller than N_g. However, as we will see below, our result changes little even if this possibility is allowed.

Let us first examine the general sensitivity of our calculation to the parameters discussed above. Figure 1 shows the abundances of "Lyman break galaxies" (N) predicted in the standard CDM model and in a flat CDM model with $\lambda_0 = 0.9$ as a function of σ_8, and compares the prediction with the observed abundance (*dotted lines*). For each model, results are shown for two extreme values of h. The difference between these results are not large for the ranges of h relevant to our discussion. The change of h has two compensating effects: an increase of h pushes the redshift (for a given Δt) of halo formation to a higher value and causes N to decrease, but at the same time enhances the power on small scales for a given σ_8 [because $\Delta(r_0)$ becomes steeper] so as to increase N. We present in Figure 1 one more set of curves for the calculation that allows a maximum number of Lyman break galaxies for a given halo, i.e., we estimate the galaxy number density by dividing the mean density of mass contained in halos with $\sigma \geq \sigma_{\rm min}$ by a mass corresponding to $\sigma_{\rm min}$. The result differs little from calculations based directly on equation (1), at least for the range of σ_8 relevant to our discussion. This means that the number of Lyman break galaxies cannot be much larger than that of halos.

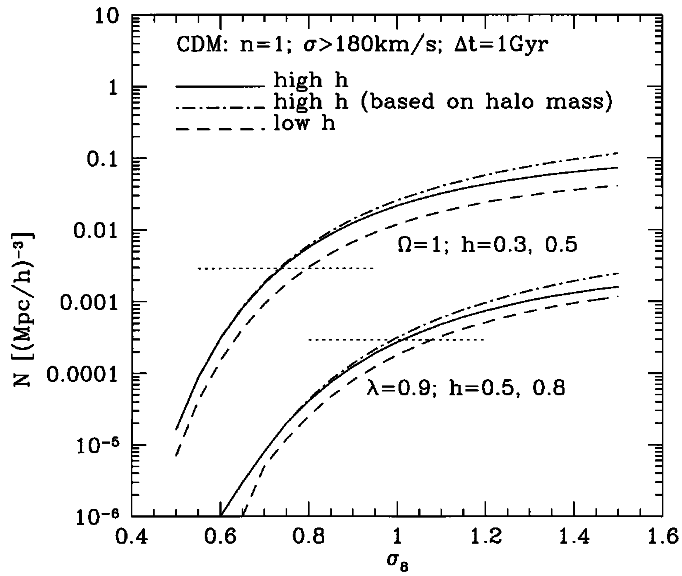

FIG. 1.—Comoving number densities of halos at $\Delta t = 1$ Gyr before the epoch of $z = 3$ predicted in the standard CDM model ($\Omega_0 = 1$) and in a flat CDM model ($\Omega_0 = 0.1$, $\lambda_0 = 0.9$). For each model, results are shown for two values of h (other parameters are fixed to be at their fiducial values), and for one case where the calculation is made to allow the maximum number of galaxies for a given halo (see text). The horizontal dotted line shows the observed abundance of Lyman break galaxies (S96) estimated for the relevant cosmology.

Our main result is summarized in Figure 2, which shows the values of σ_8 required to give the observed N_g as a function of the free parameter listed in Table 1. The two (thin) curves correspond to the calculations for the two epochs discussed in § 2. We also show by the thick lines σ_8 given by the four year *COBE* data as a function of h in Figure 2*a*, and for $h = 0.5$ and 0.8 in Figures 2*b*–2*e*. Since we take our abundance calculation as a lower limit on the required halo abundance, the allowed range lies in the lower right region of the line indicating the *COBE* normalization.

Let us now discuss each specific case. Figure 2*a* shows the constraint on h for standard CDM models ($\Omega_0 = 1$, $n = 1$). The allowed range is $h \gtrsim 0.35$ and is not very sensitive to the change of Δt. This limit is slightly higher than the upper limit

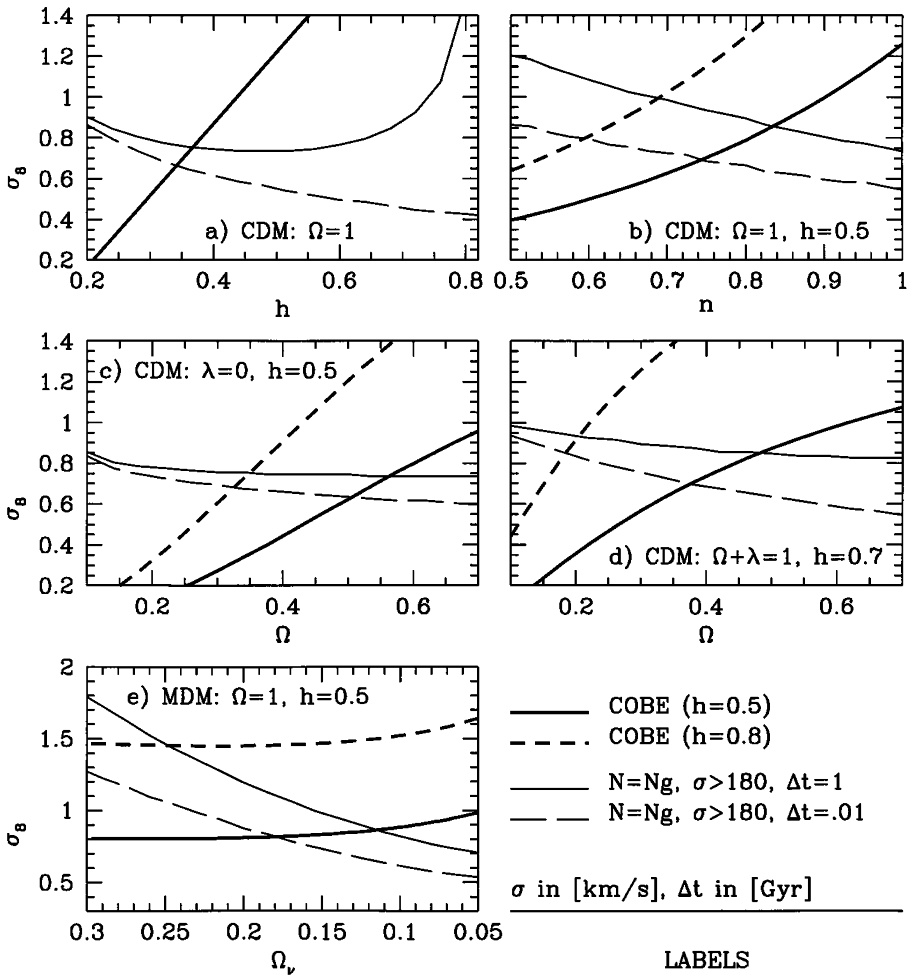

FIG. 2.—Values of σ_8 required to have the predicted halo abundance equal the observed abundance of Lyman break galaxies (N_g). The value of σ_8 given by the four year *COBE* data are shown by thick curves (when two such curves are shown, they refer to two different h). Since we require $N \geq N_g$ (see text), the allowed region is below the curve indicating the *COBE* normalization (*thick curve*). (*a–d*) CDM-like models; (*e*) MDM models.

$h < 0.3$ (so that $\Gamma \equiv \Omega_0 h < 0.3$) to give the required large-scale clustering power at $z \sim 0$ (Efstathiou, Sutherland, & Maddox 1990). For $h = 0.5$, the abundance limit gives $\sigma_8 \gtrsim 0.6$, whereas the *COBE* normalization leads to $\sigma_8 \sim 1.2$. Although there is no conflict, the gap between the two values of σ_8 implies that an order of magnitude more halos must have existed at $z > 3$ without forming stars.

Figure 2*b* gives the constraint on the power index n for tilted CDM models with $\Omega_0 = 1$ and $h = 0.5$. We obtain a limit $n > 0.85$ for $\Delta t = 1$ Gyr, and $n \gtrsim 0.75$ for $\Delta t = 0.01$ Gyr. To allow a value $n \sim 0.7$, we must take $h \sim 0.6$ and $\Delta t \ll 1$ Gyr. On the other hand, $n \sim 0.7$ and $h \sim 0.5$ seems to be required to match the observations on large scales at low z (e.g., Ostriker & Cen 1996). Such a model, therefore, is not favored by our abundance argument.

Figure 2*c* shows the results for open CDM models. The predicted abundance depends only weakly on h and calculations are shown only for $h = 0.5$. We obtain a limit $\Omega_0 \gtrsim 0.5$ for $h = 0.5$ and $\Omega_0 \gtrsim 0.3$ for $h = 0.8$. In terms of Γ, these limits can be written as $\Gamma \gtrsim 0.25$. The fact that the value of N_g is smaller and the linear density perturbations grow slower in an open universe makes the limit on Γ lower than that obtained for the Einstein–de Sitter universe. The limit we obtained is only marginally consistent with what is required to explain the large-scale clustering power.

Given in Figure 2*d* is the constraint on Ω_0 for flat CDM models. We present the abundance results for $h = 0.7$, but they depend only weakly on h. The *COBE* data leads to $\Omega_0 \gtrsim 0.4$ for $h = 0.5$. For $h = 0.8$, we obtain $\Omega_0 \gtrsim 0.2$. These limits are summarized as $\Gamma \gtrsim 0.16$–0.2. This range of Γ (or Ω_0) well overlaps with that derived from the clustering of galaxies on large scales. In particular, a flat CDM model with $\Omega_0 \sim 0.3$ and $h \sim 0.7$, as favored by Ostriker & Steinhardt (1995), is perfectly consistent with the observed abundance of giant galaxies at high redshifts.

Finally, Figure 2*e* shows the constraint on Ω_ν for MDM models with $h = 0.5$ and $\Omega_0 = 1$. We see that any MDM models with $\Omega_\nu \gtrsim 0.2$ are inconsistent with the limit if $h = 0.5$. Lower values for Ω_ν are still allowed, but the advantage of the MDM models in explaining large-scale clustering power would be lost for such a small Ω_ν (e.g., Jing et al. 1993; Klypin et al. 1993).

4. PREDICTION FOR THE CORRELATION FUNCTION

The bias parameter of dark halos, b, is defined by the ratio of the two-point correlation function of halos ξ to that of mass

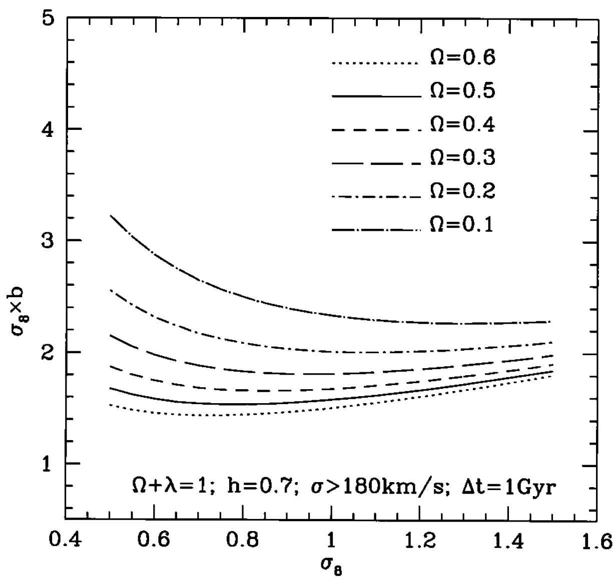

FIG. 3.—Bias parameter b (times σ_8) for the halos of "Lyman break galaxies" in flat models with various Ω_0 and σ_8. A value of $\sigma_8 b > 1$ means that these "galaxies" are more strongly correlated than present-day normal galaxies.

ξ_m as $\xi(r) = b^2 \xi_m(r)$. Mo & White (1996) argued that this bias parameter is a function of σ and z, and to the moderately nonlinear regime, it is accurately described by

$$b(\sigma, z) = 1 + \frac{1}{\delta_c(z)}\left[\frac{\delta_c^2(z)}{\Delta^2(r_0)} - 1\right]. \qquad (2)$$

This b parameter refers to the bias factor of galaxies if they formed at the center of these halos and have not lost their identities during subsequent evolution. In Figure 3 we plot $\sigma_{8,g} \equiv \sigma_8 b$ as a function of σ_8 for the Lyman break galaxies in flat CDM models, where b is the average of $b(\sigma, z)$ over $\sigma > \sigma_{\min}$ with a weight of $dN/d\sigma$. According to the above interpretation, $\sigma_{8,g}$ is the rms fluctuation of counts of these "galaxies" in spheres of radius 8 h^{-1} Mpc at present time. The value of $\sigma_{8,g}$ for present-day normal galaxies is ~1 (e.g., Davis & Peebles 1983). Figure 3 shows that "Lyman break galaxies" in these models are significantly more strongly clustered than normal galaxies. For $\Omega_0 = 0.3$ and $\sigma_8 \sim 1$, $\sigma_{8,g}$ is about 1.8. Thus, the amplitude of the correlation function of these galaxies at present time should be about 3 times as large as that of normal galaxies, or comparable to that of giant early-type galaxies (e.g., Davis & Geller 1976; Jing, Mo, & Börner 1991). This prediction corroborates the arguments that the observed Lyman break galaxies are the progenitors of present-day large E/S0 galaxies.

5. CONCLUSIONS

The abundance of giant galaxies at high redshift gives significant constraints on cosmogony models and discriminates among models that satisfy other currently available tests. Using the *COBE* normalization of the perturbation spectrum, we have shown that the abundance of Lyman break galaxies, as observed by S96, already rules out a number of current models. In particular, the CDM models that are devised to give large-scale clustering power by lowering the Hubble constant or by tilting the initial density power spectrum are disfavored, leaving the case with a low-density universe as marginally allowed. We are left with moderately Λ-dominated CDM models as the ones that best satisfy the constraints. The MDM models that can explain large-scale clustering power are also disfavored. If large-scale structure formed through hierarchical clustering, high-redshift giant galaxies should be more strongly clustered at present time than normal galaxies, corroborating the interpretation that Lyman break galaxies are progenitors of early-type giant galaxies.

The caveat is that our argument hinges on the assumption that the velocity dispersion observed by S96 is gravitational. If the high velocities are dominantly nongravitational, the conclusions we derived should all be modified, so is the interpretation given in S96. We are looking forward to the confirmation of this point in future high-resolution spectroscopy.

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