YOUNG GALAXIES: WHAT TURNS THEM ON?

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ABSTRACT

Lyman break galaxies (LBGs) at \( z \approx 3 \) exhibit number densities and clustering similar to local \( L_z \) galaxies; however, their star formation rates are much higher. We explore the scenario in which LBGs are starburst galaxies triggered by collisions and thus provide an explanation for these key properties. The relative paucity of starburst galaxies at low redshift can be attributed to a much higher collision rate in the past. We use high-resolution cosmological N-body simulations and a hierarchical halo finder to estimate the galaxy collision rate as a function of time in the popular \( \Lambda \)CDM cosmological model. We find that bright collisional starbursts are frequent enough to account for most of the high-\( z \) (2.5–4.5) LBGs. Moreover, many of the objects are of relatively small mass, but they cluster about large-mass halos. They therefore exhibit strong clustering, similar to that observed and stronger than that of the relevant massive halos.

Subject headings: cosmology: theory — dark matter — galaxies: interactions — galaxies: starburst — large-scale structure of universe — methods: numerical

1. INTRODUCTION

Data from the Hubble Deep Field (reviewed in Dickinson 1998) and ground-based telescopes (Steidel et al. 1996a, 1996b; Lowenthal et al. 1997; Steidel et al. 1999) have revealed a population of galaxies at \( z \approx 2.5–4.5 \). They were found by multicolor photometry exploiting the characteristic spectral attenuation shortward of the Lyman limit, so these galaxies are referred to as “Lyman break galaxies” (LBGs). The LBGs are observed to be abundant and highly clustered, with comoving number densities and clustering properties at \( z \approx 3 \) comparable to those of present-day bright \((\approx L_z)\) field galaxies (Giavalisco et al. 1998; Adelberger et al. 1998). They are forming stars at a high rate, comparable to local “starburst” galaxies, and are much smaller than similarly bright galaxies nearby.

There are competing views regarding the nature of LBGs. In one view (Steidel et al. 1996b; Adelberger et al. 1998; Baugh et al. 1998; Governato et al. 1998; Mo, Mao, & White 1999), most LBGs are large galaxies quiescently forming stars at the bottom of the potential wells of massive dark matter halos. We refer to this idea as the “central quiescent” scenario. An alternate view (Lowenthal et al. 1997; Somerville, Primack, & Faber 1999b) maintains that LBGs are mainly galactic starbursts triggered by collisions between small, gas-rich galaxies. We refer to this idea as the “collisional starburst” scenario.

Within the central quiescent scenario, there is roughly a one-to-one relationship between the LBGs and massive halos (Steidel et al. 1996b; Adelberger et al. 1998). This helps explain the strong clustering of observed LBGs, since in cold dark matter (CDM; Blumenthal et al. 1984) theories of hierarchical structure formation, massive objects are more clustered than low-mass objects. It has been shown that the clustering properties of LBGs at \( z \approx 3 \) can be reproduced within various CDM models if the LBGs are associated with the most massive collapsed dark matter (DM) halos at that epoch (Jing & Suto 1998; Wechsler et al. 1998; Adelberger et al. 1998). More detailed modeling appears generally consistent with the central quiescent framework (Baugh et al. 1998; Governato et al. 1998).

Until the simulations reported here, there have been no predictions for clustering properties and only rough estimates of number densities of LBGs within the collisional starburst picture. Somerville et al. (1999b) used a semianalytic treatment in order to compare the properties of individual galaxies in the two scenarios and argued that the high star formation rates, small emission-line widths (Pettini et al. 1998) (~70 km s\(^{-1}\)), young ages (Sawicki & Yee 1998), and high star formation surface densities (Lowenthal et al. 1997; Heckman et al. 1998) of LBGs are more easily explained within the collisional starburst model. However, there were many unanswered questions, since only simple approximations (Makino & Hut 1997) were used to estimate the merger rate of subhalos at high redshift \( z \approx 3 \) and there was no way to calculate the spatial distribution of collisional starbursts.

In order to establish whether collisional starbursts are a plausible origin for LBGs, we now ask whether the collisions in hierarchical scenarios can match the observed number density and clustering properties. These questions are addressed in this Letter using high-resolution N-body simulations.

2. N-BODY SIMULATIONS AND HALO/COLLISION FINDERS

Only recently have cosmological N-body simulations reached the stage at which halo substructure can be resolved (e.g., Klypin et al. 1999). Our simulations make use of the ART code (Kravtsov, Klypin, & Khokhlov 1997), which utilizes an adaptive grid to obtain the unprecedented resolution necessary for identifying collisions between well-resolved galactic halos (or subhalos) in a cosmological volume. The simulations followed the evolution of the DM in the popular \( \Lambda \)CDM model \((\Omega_m = 1 - \Omega_{\Lambda} = 0.7, H_0 = 70 \text{ km s}^{-1} \text{Mpc}^{-1}, \sigma_8 = 1.0)\). Our main results are based on a simulation run down to \( z = 1.7 \) with particle mass \( m_p = 1.3 \times 10^8 \text{ h}^{-1} \text{M}_{\odot} \) in a 30 \( h^{-1} \text{ Mpc} \) box, but we have also used another ART simulation with the same number of particles (256\(^3\)) in a 60 \( h^{-1} \text{ Mpc} \) box run to \( z = 0 \). We locate
DM halos using a maximum bound–density halo finder (Klypin et al. 1999), now extended to cope with halo interactions and substructure (Bullock 1999). Halos are modeled by the density profile (Navarro, Frenk, & White 1996) \( \rho_{\text{NFW}}(r) = \rho_s [(r/R_s)(1 + r/R_s)^2] \), which provides a characteristic radius \( R_s \), virial radius \( R_{\text{vir}} \) and mass \( M_{\text{vir}} \), and the associated fitting errors. The profile of a subhalo may be truncated short of its \( R_{\text{vir}} \). We treat only halos with \( M_{\text{vir}} > 7 \times 10^9 \, h^{-1} M_\odot \) (>50 particles). This is sufficient to resolve collisional starburst LBGs according to the luminosities assigned by our prescription (see below). Halo collisions are identified using pairs of stored simulation outputs at redshifts \( z_2 > z_1 \). For each halo at \( z_1 \), we search for sets of particles that originated in different halos at \( z_2 \). If the centers of two such sets overlap within their \( R_s \) radii at \( z_1 \), a collision is declared (Kolatt et al. 1999). Figure 1 shows the locations of such collisions.

3. FROM COLLISIONS TO BURSTS

We assume that each small DM halo at \( z \sim 3 \) contains a gas-rich galaxy at its center and that each collision results in a starburst. Mergers are included not only between isolated halos,
but also between “subhalos”—halos that reside within the virial radius of larger halos. Note that the analytic predictions for merger rates obtained by Press-Schechter approximations (Lacey & Cole 1993) are not sufficient here because they miss subhalos of isolated systems, they are limited in predicting the progenitor mass spectrum (Somerville & Kolatt 1999), and they ignore spatial correlations.

The top panel in Figure 2 shows the time evolution of the number density of identified collisions as a function of look-back time, assuming a duration of visibility $\tau_{\text{vis}} = 100$ Myr. About one-half of the collisions at $z \approx 4$ involve subhalos; such collisions would have been missed without these very high resolution $N$-body simulations, which significantly supersedes the crude treatment of collisions in the semianalytic investigation (Somerville et al. 1999b). Unbound collisions (those in which the two halos are not subsequently bound) are not accounted for at all in the semianalytic models. Also, the dynamical friction timescale used in semianalytic models tends to overestimate the host-subhalo collision timescale (Kolatt et al. 1999), the subhalo-subhalo collision approximation (Makino & Hut 1997) is somewhat simplistic, and the progenitor mass spectrum is uncertain (Somerville & Kolatt 1999; Somerville et al. 1999a). The collision rate per physical volume (not shown) declines in proportion to $(1 + z)^3$ for $z \leq 2.5$, in general agreement with theory and observations. This was determined for halos larger than $10^{11} h^{-1} M_\odot$ using our simulation in a larger volume with lower mass resolution.

To assess how many collisions should actually be observable, luminosities are assigned as follows. We assume that before a collision each galaxy has a cold-gas reservoir $m_c = f_c f_b m_{\text{baryon}}$, where $f_c$ is the fraction of mass in baryons ($f_c \equiv \Omega_c / \Omega_m$) and $f_b$ is the fraction of baryons in cold gas. We assume $\Omega_m = 0.018 h^{-2}$ and $f_b = 0.3$. Based on simulations including gas-dynamics and star formation (Mihos & Hernquist 1994a, 1994b, and our new simulations at $z \sim 3$ with $f_\text{baryon} = 0.3$ using an updated version of the same code), we divide the collisions into major ($m_c / m_\odot > 0.25$) and minor collisions and assume that during a burst of duration $\tau_{\text{burst}} = 50$ Myr, 75% and 50% of the gas is converted into stars, respectively. Gas depletion due to multiple collisions is ignored because we find that at most 4% of the matter in colliding halos at $z \geq 2$ has participated in a previous encounter. We estimate the apparent magnitude of collisional starbursts $M_\text{Ab}$ in the band equivalent to 1600 Å rest-frame, and $\tau_{\text{vis}}$, using Bruzual-Charlot (GISSEL98) stellar population synthesis models (assuming solar metallicity and a Salpeter initial mass function). The upper thick line in the bottom panel of Figure 2 shows the time evolution of the number density of observable LBGs with $M_\text{Ab} < 25.5$ for the collisional starburst model. At $z \sim 3$, only burst events involving halos larger than $8 \times 10^9 h^{-1} M_\odot$ contribute to the population of $M_\text{Ab} < 25.5$ galaxies ($>4 \times 10^9 h^{-1} M_\odot$ at $z \sim 2$). Because of compensating effects, varying both $\tau_{\text{burst}}$ and star formation efficiency by factors of 2 either way results in changes smaller than 30% in observable number density. The observed number densities of LBGs brighter than $M_\text{Ab} = 25.5$ are shown for comparison, calculated from the latest data (Pozzetti et al. 1998; Adelberger et al. 1998; Steidel et al. 1999) assuming the simulated cosmology. The predicted number densities are somewhat larger than those observed and thus allow for dust extinction, which we have not included. The arrows on the data points result from assuming a (conservative) factor of 3 in dust extinction, coupled with the $z \sim 3$ and $z \sim 4$ luminosity functions estimated by recent ground observations (Steidel et al. 1999).

For comparison, we show the predictions of a central quiescent model. We assume that every sufficiently massive halo hosts one LBG whose luminosity is tightly correlated with the halo mass, and we obtain an effective (constant) mass-to-light ratio ($M/L$) by adjusting the halo mass threshold at $z = 3$ ($M = 8 \times 10^{11} h^{-1} M_\odot$) to reproduce the observed abundance of LBGs (Steidel et al. 1999). We then predict the density evolution assuming that $M/L$ is constant with redshift (note that a larger mass threshold is required at higher $z$ for a fixed apparent magnitude limit). This type of model generically predicts a steep falloff in density toward higher $z$, in contrast with the collisional scenario and in apparent disagreement with the newest data (Steidel et al. 1999) (solid diamonds). Redshift evolution is thus a key discriminant between the scenarios. The predictions of the simple model shown here are similar to those of more detailed central quiescent models (Baugh et al. 1998), but large uncertainties remain. Very different results can be obtained if the efficiency of star formation varies with redshift (Somerville et al. 1999b).

4. CLUSTERING PROPERTIES

A key observed statistical property of the LBGs is the strong clustering they manifest. In the central quiescent model the number density of LBGs sets their mass scale. Analytic ap-
proximations (Mo et al. 1999) can then be used in order to derive their clustering properties. Here, since the collisions are selected by their dynamics, one must calculate clustering properties directly from the simulations.

Figure 3 depicts the correlation function of the collisions. In the range 1–5 h\(^{-1}\) Mpc, it can be approximated by a power law, \(\xi_c(r) \approx (r/r_0)^{-\gamma}\), with \(r_0 \approx 5 h^{-1}\) Mpc and \(\gamma = 2.6\). Shown for comparison is \(\xi_m(r) \approx (r/3.5 h^{-1}\) Mpc\(^{-2}\) for halos larger than \(10^{13.5} h^{-1} M_\odot\); these are what the central quiescent scenario would identify with LBGs. Given current uncertainties, both correlation functions are consistent with the parameters derived from observations (Adelberger et al. 1998; Giavalisco et al. 1998) for the simulated cosmology: \(r_0 \approx 6 h^{-1}\) Mpc and \(\gamma \approx 2.6\). Also shown for reference is \(\xi_m(r)\) of the underlying dark matter. The relative biases at 5 h\(^{-1}\) Mpc are \((\xi_c/\xi_m)^{1/2} = 3\) and \((\xi_c/\xi_m)^{1/2} = 2\). We find that \(\sim 30\%\) of the collisions at \(z \sim 3\) occur within halos of mass \(\sim 10^{12.5} h^{-1} M_\odot\) and that most of the rest occur in dense environments near such halos. This is consistent with the fact that the collisions are highly correlated and is confirmed by the similarity between the autocorrelation of collisions and the cross-correlation of collisions and halos of mass greater than \(10^{13.5} h^{-1} M_\odot\) at \(0.5 < r < 5 h^{-1}\) Mpc. The combination of gravitational collapse and a collision rate proportional to the square of the halo number density can explain why collisions occur mainly near the most massive halos (Fig. 1).

5. CONCLUSIONS

The results presented here provide the first quantitative results on the clustering of colliding halos at high redshift and a much more accurate measure of their number density than the earlier semianalytic calculations, which these new results generally confirm. In particular, they show that starbursts associated with collisions of relatively low-mass halos are consistent with the observed number density and clustering of bright LBGs at \(z \sim 2.5\)–4.5, at least in the \(\Lambda\)CDM cosmology; other popular cosmologies should be qualitatively similar (Somerville et al. 1999b; Wechsler et al. 1998). Finally, they predict that a key test between models is the number of LBGs versus redshift, which falls off much faster in the central quiescent scenario than for collisional starbursts. In addition to further tests, such as the luminosity function and virial mass measurements, this should ultimately distinguish between these scenarios.

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Fig. 3.—Two-point autocorrelation functions. The upper curve is for collisions between DM halos of \(M > 7 \times 10^9 h^{-1} M_\odot\) that occurred in the redshift interval \(3.9 < z > 2.9\). The error bars are combined Poisson and model fit \((R_h)\) errors. The middle curve refers to halos at \(z = 2.9\) with \(M > 10^{12} h^{-1} M_\odot\), and the lower curve is for the underlying dark matter.