The nature of high-redshift galaxies

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Abstract

Using semi-analytic models of galaxy formation, we investigate the properties of $z \sim 3$ galaxies and compare them with the observed population of Lyman-break galaxies (LBGs). In addition to the usual quiescent mode of star formation, we introduce a physical model for starbursts triggered by galaxy-galaxy interactions. We find that with the merger rate that arises naturally in the CDM-based merging hierarchy, a significant fraction of bright galaxies identified at high redshift ($z \gtrsim 2$) are likely to be low-mass, bursting satellite galaxies. The abundance of LBGs as a function of redshift and the luminosity function of LBGs both appear to be in better agreement with the data when the starburst mode is included, especially when the effects of dust are considered. The objects that we identify as LBGs have observable properties including low velocity dispersions that are in good agreement with the available data. In this “Bursting Satellite” scenario, quiescent star formation at $z \gtrsim 2$ is relatively inefficient and most of the observed LBGs are starbursts triggered by satellite mergers within massive halos. In high-resolution N-body simulations, we find that the most massive dark matter halos cluster at redshift $z \sim 3$ much as the LBGs are observed to do. This is true for both the $\Omega = 1$ CHDM model and low-$\Omega$ ΛCDM and OCDM models, all of which have fluctuation power spectra $P(k)$ consistent with the distribution of low-redshift galaxies. The Bursting Satellite scenario can resolve the apparent paradox of LBGs that cluster like massive dark matter halos but have narrow linewidths and small stellar masses.

Key words: Galaxies: formation, galaxies: evolution, galaxies: clustering, galaxies: starburst, cosmology: theory

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1 Introduction

Our window onto the high redshift universe ($z \gtrsim 2$) has been expanded tremendously by the “Lyman-break” photometric selection technique developed by Steidel and collaborators [1,2]. Similar techniques were exploited by Madau et al. [3] to identify high-redshift candidates in the Hubble Deep Field (HDF). Extensive spectroscopic follow-up work at the Keck telescope has verified the accuracy of the photometric selection technique [4,5]. The morphologies and sizes of these objects can be studied using the HDF sample [6,5], and their clustering properties can be studied using the growing sample of hundreds of Lyman-break galaxies (LBGs) with spectroscopic redshifts [7,8].

One interpretation of LBGs [2,6,7] is that they are located in the centers of massive dark matter halos ($M \sim 10^{12} M_\odot$) and have been forming stars at a moderate rate over a fairly long time-scale ($\gtrsim 1$ Gyr). This “Massive Progenitor” scenario supposes that the galaxies identified as LBGs at $z \sim 3$ are the progenitors of the centers of today’s massive luminous ellipticals and spheroids, around which the outer parts later accrete. This viewpoint has been supported by semianalytic modeling [9]. But even though the observed clustering of LBGs is very similar to that of massive dark matter halos in N-body simulations [10–12], it does not necessarily follow that the Massive Progenitor scenario is correct.

Here we consider the viability of an alternative interpretation of the observations [13,14]. There is clear observational evidence that galaxy-galaxy interactions trigger “starbursts”, a mode of star formation with a sharply increased efficiency over a relatively short timescale. There is also observational evidence that galaxy-galaxy interactions and starbursts are more common at high redshift than they are today [15]. The similarity between the appearance of the spectra of the LBGs and local starburst galaxies has been noted [5,16]. It seems likely that at least some of the observed Lyman-break galaxies are relatively low-mass ($\sim 10^9 - 10^{10} M_\odot$) objects in the process of an intense starburst, plausibly triggered by galaxy encounters. If a significant fraction of the objects are of this nature, this would have far-reaching implications for the interpretation of the observations. In this alternative “Bursting Satellite” scenario, we predict that the population of bright galaxies at high redshift would still be found in massive dark matter halos, but they would not necessarily evolve into the centers of elliptical or spiral galaxies; instead, many of them may form the low-metallicity Population II stellar halos that surround bright galaxies at low redshift [17,18], and they could also be a major source of enriched gas in massive dark matter halos. The objects that we identify as LBGs in our models have star formation rates, half-light radii, I–K colors, and velocity dispersions that are in good agreement with the available data. In Ref. [14] we also investigate global quantities such as the star formation
rate density and cold gas and metal content of the universe as a function of $z$.

2 Clustering of LBGs

The Bursting Satellite scenario predicts that LBGs are mainly in massive dark matter halos. That LBGs are associated with massive dark matter halos is a natural interpretation of the strong clustering in redshift exhibited by the LBGs [7,8]. Such halos at high redshift are expected to cluster much more strongly than the underlying dark matter, since they will be located mainly where sheets and filaments of dark matter intersect.

In order to investigate quantitatively whether this model agrees with the observed redshift clustering of the LBGs, we [12] assumed that the LBGs are associated with the most massive dark matter halos at $z \sim 3$ in a suite of high-resolution cosmological simulations [19,20] of several of the most popular CDM-variant cosmologies: standard cold dark matter (SCDM) with $\Omega = 1$, $h = 0.5$, and $\sigma_8 = 0.67$, and four COBE-normalized models: CDM with $\Omega = 1$, $h = 0.5$, and $\sigma_8 = 1.3$; cold plus hot dark matter (CHDM) with $\Omega = 1$, $h = 0.5$, and $\Omega_\nu = 0.2$ in $N\nu = 2$ species of light neutrinos; open CDM (OCDM) with $\Omega = 0.5$ and $h = 0.6$; and a flat CDM cosmology ($\Lambda$CDM) with $\Omega = 0.4$, $\Omega_\Lambda \equiv 1 - \Omega_0 = 0.7$, and $h = 0.6$. These simulations were run in 75 $h^{-1}$ Mpc boxes with 57 million cold particles and a dynamic range in force resolution of $\sim 10^3$; they thus had adequate resolution to identify all dark matter halos with a comoving number density at $z \sim 3$ higher than that of the observed LBGs. Since redshifts were measured spectroscopically [7] for only about 40% of the photometric LBG candidates, we chose a mass threshold for dark matter halos in the relevant interval in redshift in each simulation such that the comoving number density of the halos would be equal to that of the LBG candidates, and then we sampled 40% of these at random. When we compared the clustering statistics of these halos to the observed distribution of the redshifts corrected for selection, we found that the CHDM, OCDM, and $\Lambda$CDM simulations predicted that pencil beams as long and wide as the first published one [7] would have a “spike” in the redshift distribution at $z \sim 3$ as high as the one actually observed approximately 1/3 of the time, which appears consistent with the additional statistics now available [8]. However, the CDM model normalized either to clusters or to COBE had a spike as high as this less than 10% of the time. The distribution on the sky of these massive halos was very similar to that of the observed LBGs in all the simulations; i.e., they form extended structures approximately $10 h^{-1}$ Mpc across. So the spikes are not yet clusters at $z \sim 3$, but we find that they evolve into at least Virgo-size clusters by $z = 0$ (cf. [21]).

The autocorrelation function $\xi(r)$ of the massive halos that we identify with
LBGs in each simulation [12] has a power-law index of about -1.5, somewhat shallower than the -1.8 to -2.0 observed [22], and the correlation lengths that we calculate are a little larger than observed. But we expect that the agreement will improve when we take into account the higher autocorrelation of the more massive halos and the higher probability that these will host LBGs. We are presently doing this calculation combining our simulations with the semi-analytic models discussed in the next section.

3 Semi-analytic models of galaxy formation

Semi-analytic techniques allow one to model the formation and evolution of galaxies in a hierarchical framework, including the effects of gas cooling, star formation, supernova feedback, galaxy-galaxy merging, and the evolution of stellar populations. The semi-analytic models used here are described in detail in [23,24,14]. These models are in reasonably good agreement with a broad range of local galaxy observations, including the Tully-Fisher relation, the B-band luminosity function, cold gas contents, metallicities, and colors. Our basic approach is similar in spirit to the models originally developed by the Munich [25] and Durham [26] groups, and subsequently elaborated by these groups in numerous other papers (reviewed in [23,24]). We have reproduced much of the work of these groups, and improved on it in modeling the low-redshift universe in three main ways: (1) correcting the local Tully-Fisher normalization; (2) including extinction due to dust, which is crucial to get correctly both the Tully-Fisher relation (always corrected for extinction) and the luminosity function (not corrected for extinction); and (3) developing an improved disk-halo treatment of the energy and metals in supernova ejecta.

The framework of the semi-analytic approach is the “merging history” of a dark matter halo of a given mass, identified at \( z = 0 \) or any other redshift of interest. We construct Monte-Carlo realizations of the “merger trees” using an improved method [27]. Each branch in the tree represents a halo merging event. When a halo collapses or merges with a larger halo, we assume that the associated gas is shock-heated to the virial temperature of the new halo. This gas then radiates energy and cools. The cooling rate depends on the density, metallicity, and temperature of the gas. Cold gas is turned into stars using a simple recipe with the stellar masses assumed to follow the standard Salpeter IMF, and supernova energy reheats the cold gas according to another recipe. The free parameters are set by requiring an average fiducial “reference galaxy” (the central galaxy in a halo with a circular velocity of \( 220 \, \text{km s}^{-1} \)) to have an I-band magnitude \( M_I - 5 \log h = -21.7 \) (this requirement fixes the zero-point of the I-band Tully-Fisher relation to agree with observations), a cold gas mass \( m_{\text{cold}} = 1.25 \times 10^{10} h^{-2} M_\odot \), and a stellar metallicity of about solar. The star formation and feedback processes are some of the most uncertain elements of
these models, and indeed of any attempt to model galaxy formation. As in our investigation of local galaxy properties [24], we have considered several different combinations of recipes for star formation and supernova feedback (sf/fb) and also several cosmologies [14], but here we will report high-redshift results only for a single choice of sf recipe (SFR-D) and cosmology (SCDM).

### 3.1 Modeling starbursts

Previous semi-analytic models have not systematically investigated the importance of a bursting mode of star formation, particularly its effect on the interpretation of the observations of high-redshift galaxies. We start with the ansatz that galaxy-galaxy mergers trigger starbursts. This premise has considerable observational support and is also supported by N-body simulations with gas dynamics and star formation [28,29].

In our models, galaxies that are within the same large halo may merge according to two different processes. Satellite galaxies lose energy and spiral in to the center of the halo on a dynamical friction time-scale. In addition, satellite galaxies orbiting within the same halo may merge with one another according to a modified mean free path time-scale. Our modeling of the latter process is based on the scaling formula derived in Ref. [30] to describe the results of dissipationless N-body simulations in which galaxy-galaxy encounters and mergers were simulated, covering a large region of parameter space.

When any two galaxies merge, the “burst” mode of star formation is turned on, with the star formation rate during the burst modeled as a Gaussian function of the time. The burst model has two adjustable parameters, the time-scale of the burst and the efficiency of the burst (the fraction of the cold gas reservoir of both galaxies combined that is turned into stars over the entire duration of the burst). The timescale and efficiency parameters that we use are based on the simulations [28,29] mentioned above, treating major ($m_{\text{smaller}}/m_{\text{larger}} > f_{\text{bulge}} \sim 0.3$) and minor mergers separately. The quiescent mode of star formation continues as well. Details are given in [14].

Fig. 1 shows the total star formation rate for all the galaxies in a large group halo ($V_c = 500 \text{ km s}^{-1}$ at $z = 0$). The star formation rate is shown in models with: (1) no starbursts (quiescent star formation only), (2) bursts in major mergers only and satellite galaxies only allowed to merge with the central galaxy on a dynamical friction time-scale (no satellite-satellite mergers) and (3) satellite-central and satellite-satellite mergers, and bursts in both major and minor mergers. The star formation rate at high redshift is considerably amplified in model (3) compared to models (1) and (2), illustrating that neglecting satellite-satellite mergers and bursts in minor mergers will consider-
Fig. 1. The total star formation rate for all galaxies that end up within a typical halo with $V_\text{c} = 500 \text{ km s}^{-1}$ at $z = 0$. The solid line shows a model (1) with no starbursts, the dotted line shows a model (2) with mergers only between satellite and central galaxies and bursts only in major mergers, and the dashed line shows a model (3) with satellite-satellite and satellite-central mergers and bursts in major and minor mergers. The lookback time is computed for $\Omega = 1$ and $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Note that in model (3) the peaks, representing starbursts, occur primarily at lookback times of 8 to 12 Gyr (redshifts $z \sim 1 - 5$).

ably underestimate the importance of starbursts at high redshift. The “burst” models discussed in the remainder of this paper correspond to the maximal burst scenario, model (3) above. (The models of [9] are similar to (2).)

### 3.2 Comoving number density of LBGs

The first question is whether the models reproduce the observed number densities of objects at high $z$. Fig. 2 shows the comoving number density of galaxies brighter than a fixed magnitude limit as a function of redshift, over the redshift range probed by the observed LBGs. We show this function using three values for the magnitude limit: the top panel shows the abundance of bright LBGs ($m < 25.5$), the middle panel shows the abundance of galaxies brighter than 26.5, and the bottom panel shows galaxies brighter than 27.5. We have calculated the comoving number density for the ground-based sample of LBGs with spectroscopic redshifts using data from Ref. [22], and the comoving number density of LBGs at $z \sim 3$ and $z \sim 4$ from the HDF using the list of $U$ and $B$ drop-outs from Ref. [3] (see [14] for details). We note that the number density of LBGs in the HDF is considerably higher than for the ground-based sample. This may be an indication that the ground based sample is missing a
The comoving number density of galaxies brighter than $m_{\text{lim}}$, where $m_{\text{lim}} = 25.5$ (top panel), 26.5 (middle panel), or 27.5 (bottom panel). The hexagon indicates the comoving number density of LBGs with spectroscopic redshifts from the ground-based sample of [22] and the stars indicate the number density of U ($z \sim 3$) and B ($z \sim 4$) drop-outs in the HDF [3]. Bold solid lines show the comoving number density of galaxies in the models with starbursts; light solid lines show the results of the no-burst models. Dashed lines show the result of reducing the flux of each galaxy by a factor of three to estimate the effects of dust extinction [16].

substantial number of objects, or it may indicate that the small HDF volume probed by the U and B dropouts is an unusually overdense region.

Fig. 2 shows that models without bursts underpredict the number density of galaxies, especially at the brightest magnitude limit $m = 25.5$. Burst models reproduce or exceed the observed number densities of LBGs when dust extinction is neglected. The inclusion of starbursts causes a bigger change in the comoving number density of LBGs at higher redshifts and at brighter magnitude limits; i.e., the number densities in the burst models tend to have flatter dependences on both redshift and magnitude. By a redshift of $z \lesssim 2$, including starbursts has little effect on the number counts. The galaxy-galaxy merger rate is larger at high redshift because the halos are denser, and the starbursts are more dramatic because these galaxies are relatively gas rich.

The inclusion of dust is an important correction. The observed colors of the LBGs, as well as comparison of the UV to H$\beta$ fluxes, indicate that there is
almost certainly some dust in these galaxies [16,31,32]. However, the amount of dust and the resulting extinction are quite uncertain. These depend on the metallicity and age of the galaxy, the geometry and “clumpiness” of the dust, and the wavelength dependence of the attenuation law. The correction factors for the UV rest frame luminosity suggested in [16,31,32] range from \( \sim 2 \) to \( \sim 7 \). More dramatic corrections, as large as a factor of \( \sim 15 \), have been suggested [33,34].

Our estimates of the effect of dust in Fig. 2 simply decrease the luminosity of each galaxy by a factor of three. However, according to any physical dust model, a uniform correction by a fixed factor is probably unrealistic. If dust traces metal production (and hence star formation activity), more intrinsically luminous galaxies will be more heavily extinguished. It seems unavoidable that this will further increase the deficit of bright galaxies in the no-burst models seen in Fig. 2. However, if most of the bright galaxies are starbursting objects, as in the burst models, the situation is less clear. Observations [35,36] indicate that the wavelength dependence of the attenuation due to dust is “greyer” (less steep) in the UV for local starburst galaxies than a Galactic or SMC-type extinction curve. Powerful starbursts could blow holes in the dust, especially in small objects, perhaps ejecting the dust (along with metals) out of the galaxy. On the other hand, regions of active star formation may be completely enshrouded in dust, leading to even stronger extinction. In any case, models without starbursts appear to have no hope of reproducing the observed abundance of bright LBGs with just the conservative factor of three correction for dust included in Fig. 2. Even our models including starbursts do not reproduce the observed abundance of the brightest HDF LBGs with this dust correction. Since the light observed in the visible was emitted as ultraviolet in the rest frame, changing from the assumed Salpeter IMF to one with more high-mass stars can significantly increase the predicted abundance of bright LBGs. However, even such top-heavy IMFs will probably not be sufficient to save the no-burst models, which also predict a LBG luminosity function that is too steep compared to observations [14].

3.3 Line-widths, ages, and masses

The velocity dispersions of observed LBGs can be estimated based on the widths of stellar emission lines such as H\( \beta \) or O[III]. Emission lines have been detected for a few of the brightest LBGs from the ground-based sample. The velocity dispersions \( \sigma \) derived from the observed linewidths are \( \sigma = 80 - 90 \) km s\(^{-1} \) for four objects, \( 50 \) km s\(^{-1} \) for one object, and \( 150 \) km s\(^{-1} \) for one object [37]. These values agree well with the burst models, for which the probability distribution for \( \sigma \) of the stars in a disk geometry peaks at \( \sim 80 \) km s\(^{-1} \), but are in strong disagreement with the no-burst models, which
peak at $\sigma \sim 180 \text{ km s}^{-1}$.

These measurements may be affected by several biases, which remain to be unravelled. First, the observed data refer to bright LBGs, which may have systematically higher linewidths. This effect would increase the discrepancy with no-burst models mentioned above. The modelling of the velocity dispersion at the small radii probed by the observations (approximately the half-light radius) is also uncertain because of the uncertain morphology of the observed LBGs (disk vs. spheroid). This should be studied with high-resolution narrowband imaging. Still, overall the present $\sigma$s suggest small galaxies whose brightnesses are being amplified temporarily by starbursts.

The ages and stellar masses of the burst models [14] also agree well with recent estimates based on observed SEDs including IR photometry. LBG colors are well fit by young ($< 0.1 \text{ Gyr}$) stellar populations with moderate amounts of dust [34]. These young ages imply that stellar masses are also low ($\sim 10^9 M_\odot$). The LBGs in our no-burst models (and also Ref. [9]) are systematically older and more massive than the data indicate. More photometry and spectra of LBGs will help to clarify whether our models including “Bursting Satellites” adequately describe the properties of the LBGs.

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