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THE STAR FORMATION RATE-DENSITY RELATIONSHIP AT REDSHIFT THREE

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ABSTRACT

We study the star formation rate (SFR) as a function of environment for UV selected Lyman break galaxies (LBGs) at redshift three. From deep ($\mu_{I,AB}(sky) \simeq 27.6$) *UBVI* KPNO 4-m/MOSAIC images, covering a total of 0.90 deg², we select 334 LBGs in slices 100h⁻¹ Mpc (co-moving) deep spanning the redshift range 2.9 < z < 3.4 based on Bayesian photometric redshifts that include the I magnitude as a prior. The slice width (100h⁻¹ Mpc) corresponds to the photometric redshift accuracy ($\Delta_z \sim 0.15$). We used mock catalogs from the GIF2 cosmological simulations to show that this redshift resolution is sufficient to statistically differentiate the high density from the low density regions using Σ_5 , the projected density to the 5th nearest neighbor. These mock catalogs have a redshift depth of 110h⁻¹ Mpc, similar to our slice width. The large area of the MOSAIC images, $\sim 40 \times 40$ Mpc (co-moving) per field, allows us to measure the SFR from the dust-corrected UV continuum as a function of Σ_5 . In contrast to low-redshift galaxies, we find that the SFR (or UV luminosity) of LBGs at $z = 3$ shows no detectable dependence on environment over 2 orders of magnitude in density. To test the significance of our result, we use Monte Carlo simulations (from the mock catalogs) and the same projected density estimators we applied to our data. We find that we can reject the steep $z = 0$ SFR-density at the 5- σ level. We conclude that the SFR-density at $z = 3$ must be at least 3.6 times flatter than it is locally, i.e. the SFR of LBGs is significantly less dependent on environment than the SFR of local star-forming galaxies. We find that the rest-frame UV colors are also independent of environment.

Subject headings: cosmology: observations — galaxies: high-redshift — galaxies: evolution

1. INTRODUCTION

There is a long history of results showing that galaxy properties vary as a function of environments such as the morphology-density relation in clusters (Melnick & Sargent 1977; Dressler 1980; Postman & Geller 1984; Dressler et al. 1997; Treu et al. 2003) and its associated star formation rate-density relation (e.g. Lewis et al. 2002). Lewis et al. (2002) used the 2dF galaxy redshift survey (2dFGRS, Colless et al. 2001) to show that the anti-correlation between SFR and local projected density holds in clusters up to two virial radii from the cluster center. Not only is the mean luminosity a function of environment (Blanton et al. 2003; Hogg et al. 2003; Balogh et al. 2004), but the luminosity function (LF) is also a continuous function of the local density (e.g. Croton et al. 2004).

The star formation rate (SFR) depends on the local density also in groups and in the field. Gómez et al. (2003) showed similar results using the early data release (EDR, Stoughton & et al., 2002) of the Sloan Digital Sky Survey (SDSS), and showed that the SFR-density relation also holds for field galaxies. Balogh et al. (2004) used both the 2dFGRS and the SDSS to show that the SFR (as measured by the H α equivalent width) of field galaxies is strongly dependent on the local projected density. All these results point to the existence of physical mechanisms that quench star formation as the local density increases, from field to

groups to clusters.

At $z = 0.4$, the quenching of star-formation is apparently already in place. Using the wide-field ($\sim 30'$) imager SuprimeCam at the SUBARU 8-m telescope, Kodama et al. (2001) selected members of the $z = 0.41$ cluster A851 using photometric redshifts and found that the colors of faint galaxies are strongly dependent on the local galaxy density. Follow-up narrow band H α imaging of this cluster showed that the fraction of star-forming galaxies is a strong function of the local projected density far ($\gtrsim 1h^{-1}$ Mpc) from the cluster center (Kodama et al. 2004).

No observations of the SFR-density relation have yet been made at redshifts greater than one. Here, we used ground-based data from the Kitt Peak 4-m telescope fitted with the MOSAIC wide-field imager to investigate whether or not the SFR-density relation already existed at redshift $z = 3$. We use photometric redshifts that are accurate to $\delta_z \sim 0.15$ or $\sim 100h^{-1}$ Mpc, comparable in co-moving distance to those of the COMBO-17 survey.

We present our data and briefly discuss our selection of LBGs in section 2. We then use mock catalogs from the GIF2 collaboration (Gao et al. 2004) to show in section 3 that our photometric redshift accuracy is sufficient to statistically distinguish between low and high density regions. We estimated the SFR as in section 4. Finally, our results

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are presented in section 5 and conclusions in section 6.

Throughout this paper, we adopt $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ and $H_o = 100h$ km s $^{-1}$ Mpc $^{-1}$. At redshift $z \sim 3$, $H(z) \sim 4.46H_o$, so $\delta z = 0.1$ corresponds to $67h^{-1}$ Mpc in co-moving coordinates.

2. DATA

The observations used here are described in detail in Bouché (2003) and Bouché & Lowenthal (2004) (hereafter BL04). Briefly, we used the wide-field MOSAIC camera (Jacoby et al. 1998) at the Kitt Peak National Observatory 4m telescope to image three fields in *UBVI* to limiting magnitude $\mu_{I,AB}(sky) \simeq 27.6$. These fields were selected for the presence of a DLA at $z \sim 3$ in our original DLA survey (Bouché & Lowenthal 2003, BL04). Given the camera’s field of view of $36' \times 36'$ (or $\sim 40h^{-1}$ Mpc on a side), our survey covers a total of 0.90 deg 2 . We selected $\sim 3,000$ LBGs within the redshift range $2.8 < z_{\text{phot}} < 3.5$. From Monte Carlo simulations, our 50% completeness level is $I_{AB} = 24.8$ ($\mathcal{R} \simeq 25$), corresponding to $\sim 0.7L^*$, using $L^*(z = 3)$ from Steidel et al. (1999).

Photometric redshifts were obtained from the algorithm Hyperz (Bolzonella et al. 2000) coupled with the prior likelihood distribution given by the magnitude m_I of each galaxy (as in Benítez 2000). See Bouché (2003) and BL04 for a detailed description of the tests we performed on the algorithm using spectroscopic redshifts in the HDF-N. Up to $z < 6$, the overall rms Δ_z is 0.1 – 0.15 , corresponding to ~ 67 – $100h^{-1}$ Mpc and $\Delta_z/(1 + z_{\text{spec}})$ is 0.06 .

In order to selected LBGs in a narrow redshift slice, we used the criterion:

$$P(z_0 \pm W_z/2) > 0.5, \quad (1)$$

where z_0 is the slice redshift, W_z is the redshift slice width, and $P(z)$ is the redshift probability distribution (BL04). We choose a redshift width of $W_z = 0.15$ because, as discussed in Bouché & Lowenthal (2003), it produces the largest sample in the smallest redshift slice, given the rms of the photo- z ’s. At $z_0 = 3$, there are 68, 162, & 104 galaxies in our three fields for a total of 334.

3. CAN WE USE PHOTOMETRIC REDSHIFTS TO MEASURE Σ_5 ?

Before investigating the galaxy properties as a function of environment, we used the GIF2 numerical simulations of galaxy formation (described in Gao et al. 2004 and De Lucia, Kauffmann, & White 2004) to investigate whether or not, with such a coarse redshift resolution, one can make reliable density estimations based on projected surface densities. These N-body simulations were run with 400^3 particles (each $1.73 \times 10^9 M_\odot$) over a periodic cube of $110h^{-1}$ Mpc on a side in a Λ dominated universe. From the output at $z = 3$ containing $\sim 29,000$ galaxies, we simulated an LBG sample by selecting 975 objects with $m_I < 25$ and $(B - V) < 0.2$, where m_I is the observed I magnitude given the absolute magnitude M_I , the redshift of the simulation $z = 3$, and the K -correction according to the SED type of the galaxy.

Fig. 1 shows the two-dimensional distribution (projected along the z -axis) of simulated LBGs (open triangles) along

with all the galaxies (points) in the simulated GIF2 volume. One sees that the simulated LBGs do trace the major over-dense regions and filaments. Importantly, this ‘slice’ width corresponds to our redshift resolution, i.e. $\sim 100h^{-1}$ Mpc.

Fig. 2 shows, for the GIF2 simulation, the two-dimensional surface density, Σ_5 , versus the three-dimensional true density ρ_5 . Both Σ_5 and ρ_5 are computed from the distance to the 5th nearest neighbor. The horizontal error bars reflect the 1σ rms to the mean. One order of magnitude change in Σ_n corresponds to about 1.5 orders of magnitude in ρ_n . Thus, we conclude that the projected density gives a statistical measure of the true 3D over-density even when it is projected over $110h^{-1}$ Mpc.

4. ESTIMATING STAR FORMATION RATES

As reviewed by Kennicutt (1998), one can estimate the SFR from the rest-frame UV luminosity density L_ν in the range 1500 – 2500\AA :

$$\text{SFR}(M_\odot \text{ yr}^{-1}) = 1.4 \times 10^{-28} L_\nu (\text{ergs s}^{-1} \text{ Hz}^{-1}) \quad (2)$$

for a Salpeter IMF, covering the range 0.1 to $100M_\odot$. This relation applies only to galaxies with continuous star formation over time scales of 10^8 years or longer. Pettini et al. (2001) have shown that for a small sample of LBGs, estimates of SFR from Eq. 2 are consistent with the SFR inferred from $H\beta$ line fluxes.

We estimated the rest-frame luminosity densities (in ergs s $^{-1}$ Hz $^{-1}$) of the 334 LBGs in our MOSAIC images from the standard expression $f_\nu = 10^{(0.4(m_{AB} + 48.6))} / (1 + z_{\text{phot}})$ and from the luminosity distance. The luminosity was corrected for dust extinction. The amount of dust extinction (A_V) is estimated simultaneously with the estimation of the photometric redshift z_{phot} . However, we found, using mock catalogs, that A_V recovered by Hyperz is biased: $A_V(\text{true}) = 0.51 A_V + 0.32$. These mock catalogs were created from the same galaxy templates, with the same extinction law used in the redshift fitting and restricted to our redshift range of interest $2.85 < z < 3.25$.

We used the I-band ($\lambda_c = 8214\text{\AA}$) flux to estimate the SFR; this filter corresponds to rest-frame 2000\AA for $z = 3$ galaxies. We used the Calzetti et al. (2000) extinction curve³ to estimate $A_{2000\text{\AA}}$ and the dust corrected SFR (SFR_o) follows from $L_{\nu,o} = L_\nu \times 10^{0.4 A_\nu}$ and Eq. 2.

5. RESULTS & DISCUSSION

For galaxies at $z_{\text{phot}} = 3 \pm 0.075$ selected with Eq. 1, Fig. 3 shows the dust-corrected star formation rate (SFR_o) as a function of the normalized local density $\Sigma_5 / \langle \Sigma_5 \rangle$ where Σ_5 is the surface density within the 5th nearest neighbor, i.e. $\Sigma_5 = 6/(\pi r_5^2)$, and $\langle \Sigma_5 \rangle$ is its median in each of our three MOSAIC fields. The local over-density δ_5 is $\Sigma_5 / \langle \Sigma_5 \rangle - 1$. We use the normalized density in order to combine our several fields given that they do not contain the same mean number of LBGs per unit area. Error bars are shown for 20 randomly selected galaxies. There is no detectable difference between the distribution of SFRs of LBGs in low-density environments and those in high-density environments.

We used the Kolmogorov-Smirnov (KS) test to determine whether or not the galaxies in high density regions

³ This is the same extinction law that was used by Hyperz in determining the photometric redshifts.

with $\delta_5 > x$ are a random subset of those at $\delta_5 < 0$, i.e. they have the same SFR distribution. The top panel of Fig. 3 shows that we cannot reject the null hypothesis: the sample with $\delta_5 < 0$ and with $\delta_5 > 0$ are indistinguishable. Similarly, a Pearson correlation test gives a P-value $P = 0.67$. In other words, there could be a correlation only at the 32% confidence level. We repeated the analysis for higher redshift slices, ($z_0 = 3.1, 3.2, \& 3.3$) and find similar results.

Using the GIF2 simulations of section 3, we performed Monte-Carlo simulations to test whether or not the scatter in the Σ_5 - ρ_5 relation is responsible for our null-result. We selected randomly about a third of the simulated LBGs to match our sample size of 334 LBGs. These simulated LBGs were assigned a SFR using $\text{SFR}_{\text{sim}} = (\rho_5 / \langle \rho_5 \rangle)^s \times \langle \text{SFR} \rangle$, where ρ_5 is as in Fig. 2, s is the slope of the simulated SFR-density relation, and $\langle \text{SFR} \rangle$ is the observed mean SFR in our data. Noise with the same properties as in the data (i.e. $\sigma(\text{SFR}) \propto \text{SFR}$) was added to SFR_{sim} . Note that these mock catalogs have the scatter between Σ_5 and ρ_5 (Fig. 2) built in. We repeated our analysis of SFR_{sim} vs. Σ_5 1000 times for values of s spanning $[-0.5, 0.1]$.

At $z = 0$, the SFR decreases by a factor of 5 over 2 decade in density (Gómez et al. 2003; Balogh et al. 2004), i.e. $s \simeq \log(1/5)/2 \simeq -0.35$. In this case, the Pearson correlation test gives a probability smaller than 10^{-6} (or $\sim 5\text{-}\sigma$) to find no correlation. Even if we artificially increase the noise by a factor as large as 2.5, as if we had underestimated our errors by such a factor, we find there is less than 0.1% chance to find no correlation if the $z = 3$ SFR-density relation were as steep as at $z = 0$. If the $z = 3$ SFR-density relation were not as steep, but 3.6 times flatter ($s = -0.07$), we should still have detected a correlation at the $2\text{-}\sigma$ level.

As advocated by Hogg et al. (2003), because the local density has a signal-to-noise much lower than the other physical quantities, it may be preferable to compute the mean density at constant galaxy properties (e.g. SFR, M , color, etc). The left panel of Fig. 4 shows the over-density δ_5 as a function of SFR. The running median and the $1\text{-}\sigma$ spread are shown by the thick line and the error bars, respectively. Again, this plot reveals no evidence for a SFR-density relation.

We also investigate the dependence of galaxy color on density. The right panel of Fig. 4 shows the over-density δ_5 as a function of the observed-frame $V - I$. Again, the running median and the $1\text{-}\sigma$ spread are shown. The rest-frame UV colors of LBGs do not appear to change with environment. We note that this non dependence of rest-frame UV color for blue galaxies such as LBGs is similar to the results of $z = 0$ surveys: in contrast to galaxies on the red sequence (e.g. Bell et al. 2004), the mean color of blue galaxies is only weakly dependent on environment (Blanton et al. 2003; Hogg et al. 2003, 2004; Balogh et al. 2004). However, we cannot rule out an environment dependence of the mean *rest-frame* optical colors (or age)

of LBGs (e.g. Steidel et al. 2005) given that we sample only $\lambda_{\text{rest}} \lesssim 2000\text{\AA}$. Future rest-frame optical observations should address possible variations of the rest-frame optical colors of LBGs with environment.

6. SUMMARY AND CONCLUSIONS

From our wide-field images, covering a total of 0.90 deg^2 , we selected $z \simeq 3$ LBGs in several redshift slices $100h^{-1} \text{ Mpc}$ (co-moving) deep spanning the redshift range $2.9 < z < 3.4$. We computed the SFR from the UV luminosity at $\lambda_{\text{rest}} 2000\text{\AA}$. Using mock catalogs from the GIF2 simulations, we show that our photometric redshift accuracy is sufficient to statistically distinguish between low and high density regions using projected density estimators such as the density within the 5th nearest neighbor Σ_5 . Our main results are: we find that (1) there is no evidence for a SFR-density relation at $z = 3$, and (2) the rest-frame UV colors of LBGs do not appear to change with environment.

Using Monte-Carlo simulations and the same projected density estimators we applied to our data, we find a probability smaller than 10^{-6} to find no correlation if the steep $z = 0$ SFR-density were present in our data. If the $z = 3$ SFR-density relation were about four times flatter than the $z = 0$ relation, we should still have detected a correlation at the $2\text{-}\sigma$ level. We conclude that, unless the $z = 3$ SFR-density is even flatter, we would have detected it in our data. This is in sharp contrast to surveys at $z = 0$ and $z \sim 0.4$ that have shown that the mean SFR is strongly dependent on the local galaxy density (e.g. Lewis et al. 2002; Gómez et al. 2003; Balogh et al. 2004; Kodama et al. 2004).

Very few predictions have been made of how the SFR-density relation should evolve from $z \simeq 3$ to the present. Recently, Kereš et al. (2004), using SPH cosmological simulations, showed that the SFR-density relation is expected to be present as early as $z \sim 2$, but not at $z \sim 3$ (their Fig. 13). See Kereš et al. (2004) and Birnboim & Dekel (2003) for a detailed description of the physical mechanisms at play. Our observed non-dependence of SFR on environment supports the theoretical results of Kereš et al. (2004).

Naturally, our sample is not representative of the entire galaxy population at $z = 3$; it is biased towards blue star-forming galaxies and does not include the red population unveiled by the FIRES survey (Labbé et al. 2003). With the present data, we are unable to rule out the existence of a SFR-density relation if one were to include this redder population.

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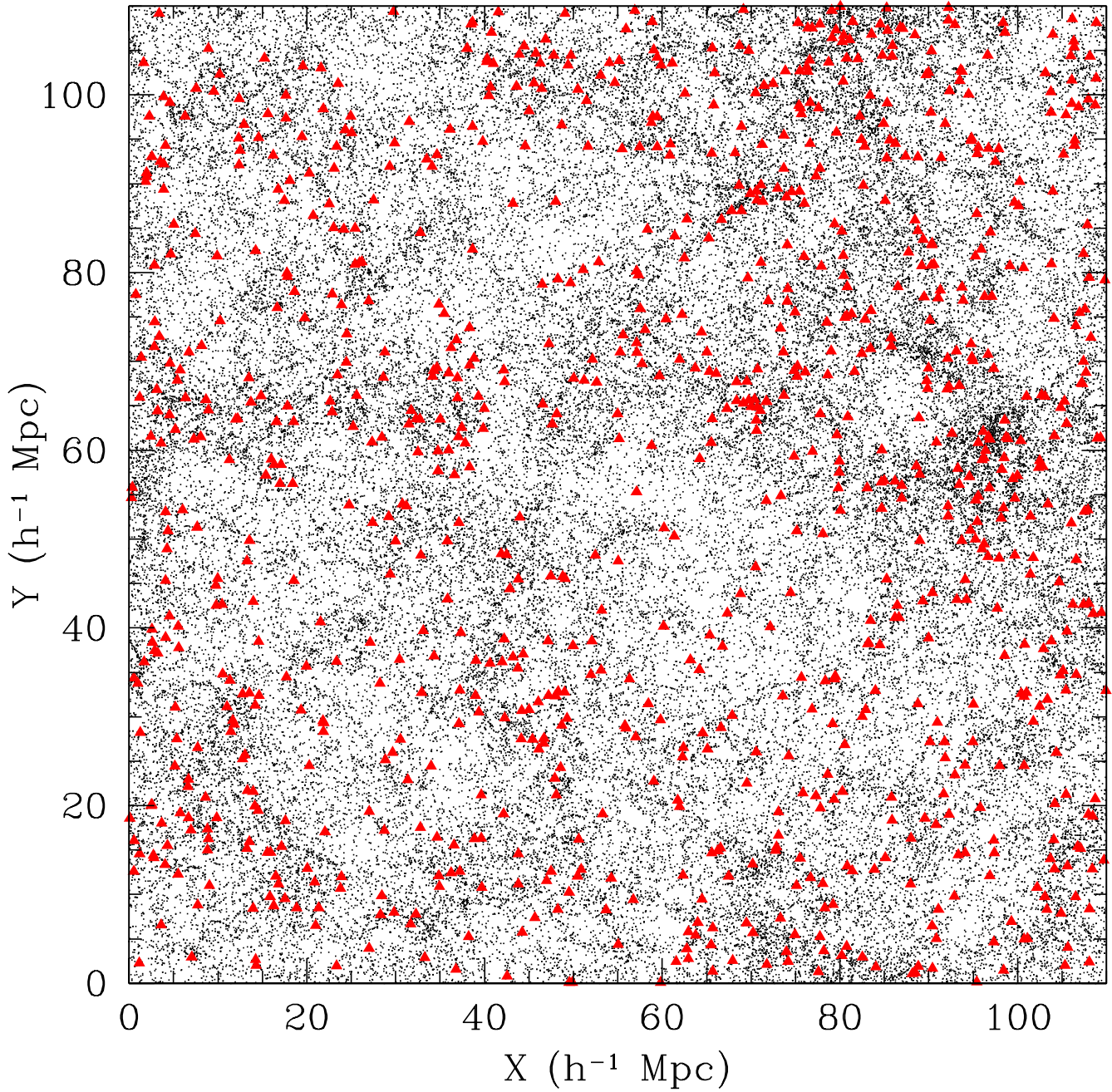


FIG. 1.— The X-Y distribution (dots) of 50% (randomly selected) of the simulated galaxies of the GIF2 simulations (Gao et al. 2004). Filled triangles show all the simulated LBGs. Features of large scale structure are visible in the simulated LBG population even though the galaxy positions are projected along the z -direction over $\sim 100h^{-1}$ Mpc. This is quantified in Fig 2.

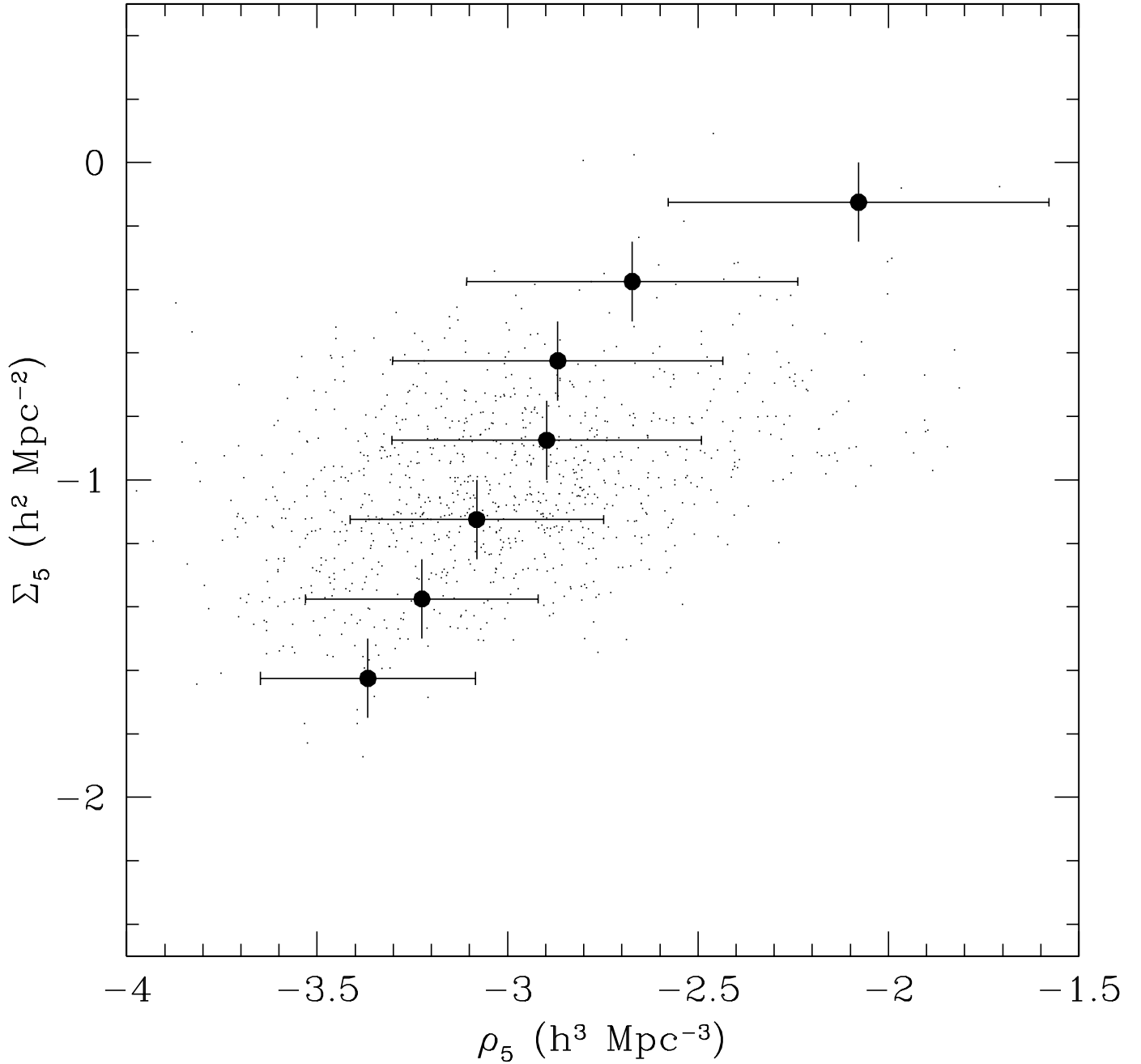


FIG. 2.— For simulated LBGs in the GIF2 simulation, the projected 2D density Σ_5 is plotted as a function of the 3D density ρ_5 . Both Σ_5 and ρ_5 are computed from the 5th nearest neighbor. The points with error bars show the mean ρ_5 and its spread (rms) in bins of Σ_5 . This shows that, even over $110h^{-1}$ Mpc, one can discriminate *statistically* between low and high density regions using projected density estimators such as Σ_5 .

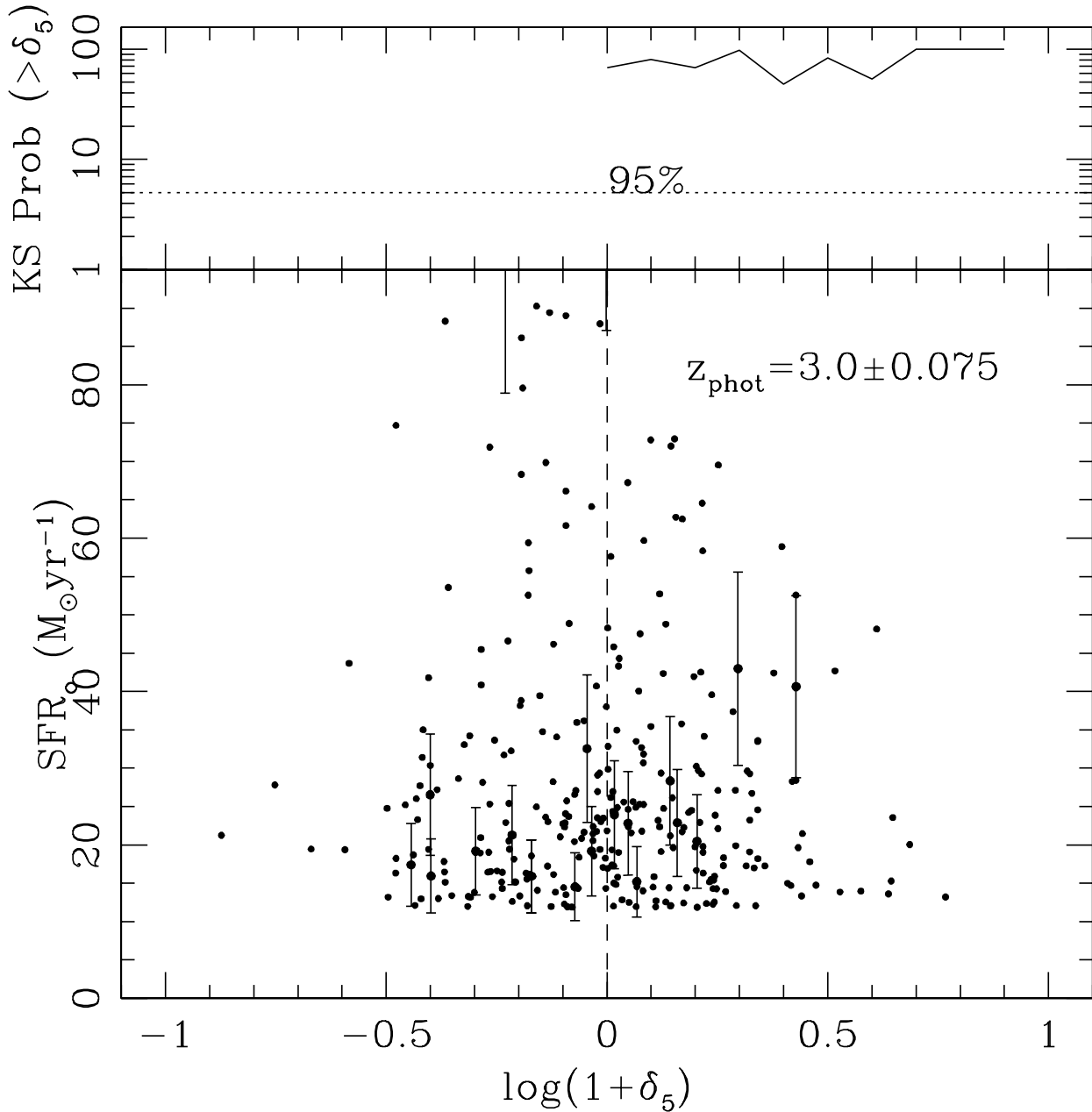


FIG. 3.— Bottom: For LBGs selected to be at $z_{\text{phot}} = 3.0 \pm 0.075$ (see text), we plot the dust-corrected SFR_o against the over-density δ_5 obtained from Σ_5 , the surface density within the 5th nearest neighbor. Error bars on SFR are shown for 20 (randomly selected) LBGs. Top: Results for the KS-test. For a given over-density δ_5 , the probability that the distribution of galaxies with over-densities $> \delta_5$ is drawn from the reference distribution (defined as $\delta_5 < 0$, left of the vertical dashed line) is shown. The distribution in the high density bins is statistically the same as in the low density bins (the 95% rejection level is indicated by the dotted line).

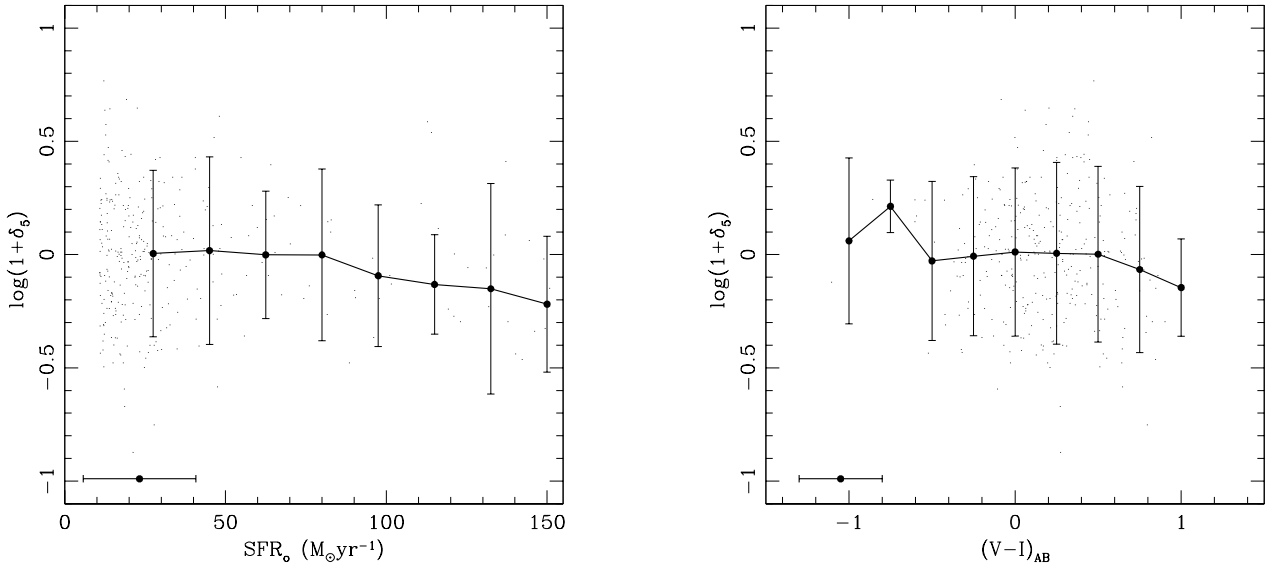


FIG. 4.— Left: The density-SFR relation at $z = 3$. The solid circles show the median over-density δ_5 in bins of SFR_o (bin size shown by the horizontal error bar). Right: The density-color relation at $z = 3$. The solid circles show the median over-density δ_5 in color bins (bin size shown by the horizontal error bar). In both panels, the thick line shows the running median, and the vertical error bars the 1- σ spread, respectively. The colors and SFR of LBGs are independent of the surrounding galaxy density.