STATISTICAL PROPERTIES OF LYMAN BREAK GALAXIES AT z ≃ 4

M. OUCHI¹, K. SHIMASAKU¹,², S. OKAMURA¹,², M. DOI¹,³, H. FURUSAWA¹, M. HAMABE⁴, M. KIMURA⁵, Y. KOMIYAMA⁶, M. MIYAZAKI¹, S. MIYAZAKI², F. NAKATA¹, M. SEKIGUCHI⁵, M. YAGI⁷, and N. YASUDA⁷
¹Department of Astronomy, School of Science, University of Tokyo, Tokyo 113-0033, Japan
²Research center for the Early Universe, University of Tokyo, Tokyo 113-0033, Japan
³Institute of Astronomy, School of Science, University of Tokyo, Tokyo 181-0015, Japan
⁴Department of Mathematical and Physical Sciences, Japan Women’s University, Tokyo, Japan
⁵Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582
⁶Subaru Telescope, National Astronomical Observatory, 650 N.A’ohoku Place, Hilo, USA
⁷National Astronomical Observatory, Mitaka, Tokyo 181-8588, Japan

Abstract. We study the luminosity function and the correlation function of about 1200 z ≃ 4 Lyman break galaxies (LBGs) with i’ < 26 that are photometrically selected from deep BRI’ imaging data of a 618 arcmin² area in the Subaru/XMM-Newton Deep Field taken with Subaru Prime Focus Camera. The contamination and completeness of our LBG sample are evaluated, on the basis of the Hubble Deep Field-North (HDF-N) objects, to be 17% and 45%, respectively. We derive the UV (rest 1700 Å) luminosity functions (LFs) and find a large population of UV-luminous galaxies at z ≃ 4. The LFs of the red and blue subsamples imply that the bright LBGs are redder in the UV continuum than the average color of the LBGs. Then we calculate the correlation function over \( \theta = 2'' - 1000'' \) and find that it is fitted fairly well by a power law, \( \omega(\theta) = A_\omega \theta^{-0.8} \), with \( A_\omega = 0.71 \pm 0.26 \). We estimate the correlation length \( r_0 \) (in comoving units) of the two-point spatial correlation function \( \xi(r) = (r/r_0)^{-1.8} \) to be \( r_0 = 2.7^{+0.5}_{-0.6} h^{-1}\text{Mpc} \) \( (\Omega_m = 0.3 \text{ and } \Omega_\Lambda = 0.7) \). The correlation function shows an excess of \( \omega(\theta) \) on small scales \( (\theta \lesssim 5'') \), departing from the power-law fit at > 3σ significance level. Interpreting this as being due to galaxy mergers, we evaluate the fraction of galaxies undergoing mergers to be 3.0 ± 0.9%, which is significantly smaller than those of galaxies at intermediate redshifts.

1 Introduction

In the past several years, deep field surveys have made remarkable breakthroughs in studies on high redshift galaxies. The most successful survey would be the Hubble Deep Fields which are deep enough to study high-z galaxies up to \( z \simeq 6 \). Many efforts on spectroscopic and photometric follow-up observations reveal hundreds of high-z galaxies and their properties (e.g. [8]). However, the surveyed areas of HDFs are as small as a few arcmin² each, so they may be affected by field-to-field variations. Steidel and his collaborators have pioneered in statistical studies of high-z galaxies based on ground-based wide survey data [24]. They isolate high-z galaxies in a two-color plane using the UV continuum features, and galaxies selected in this way are called Lyman break galaxies (LBGs). They studied the number density [21], the spatial distribution [6], nebular emission lines [18], and the stellar population [15]. Most of their studies are based on \( z \sim 3 \) LBG samples which were selected using \( U_0GR \) colors. In this contribution, we extend the study to \( z \sim 4 \) LBGs based on our BRI’ data taken with a newly installed Subaru Prime Focus Camera (Suprime-Cam: [14]), which is a unique wide-field imager mounted on the 8m Subaru Telescope. Throughout this contribution, magnitudes are in the AB system, and all calculations assume a Λ-dominated spatially flat cosmology, \( (\Omega_m, \Omega_\Lambda) = (0.3, 0.7) \).

2 Observations and Data Reduction

Deep and wide-field \( B_rV_rR_r \), and \( i’\)-band imaging data of a central 30’ \times 24’ area in the Subaru/XMM-Newton Deep Survey Field \((2^{h}18^{m}00^{s}, -5^\circ12'00''[J2000]) \) were taken with Suprime-Cam during the commissioning observing runs on 2000 November 24-27. The present work is based on the \( B,R \), and
Figure 1: Left panel: $B - R$ vs. $R - i'$ color diagram displaying the colors of model galaxies and stars. Typical spectra of elliptical, Sbc, Scd and irregular galaxies [4] are redshifted from $z = 0$ to $z = 3$, which are shown by four dashed lines. Each line has filled circles at $z = 0, 1, 2$ and 3. We use a typical spectrum of galaxies at $z \simeq 3$ to compute the $z \sim 4$ galaxy track which is shown by the solid line [13]. Star marks are 175 Galactic stars given by [7]. The arrow expresses the direction and magnitude of dust extinction on the $B - R$ vs. $R - i'$ plane for $E(B - V) = 0.15$, when Calzetti’s extinction law [3] is applied. The box surrounding the upper left region is the selection criteria of our $z \sim 4$ galaxies (equation 1). No obvious contaminant is found within the box.

Right panel: $B - R$ vs. $R - i'$ color diagram displaying the colors of 5 $\sigma$ detected objects in our data. The box for our selection criteria is also shown.

$i'$ data. The individual CCD data were reduced and combined using IRAF and the mosaic-CCD data reduction software developed by us [23]. The final images cover a contiguous 618 arcmin$^2$ area with a point-spread function FWHM of 0.98. The net exposure times of the final images are 177, 58, and 45 minutes for $B$, $R$, and $i'$, respectively. The limiting magnitudes are $B = 27.6$, $R = 26.5$, and $i' = 26.2$ for a 3$\sigma$ detection in a 2$''$ diameter aperture. The $i'$-band frame is chosen to detect objects, and we limit the object catalog to $i' \leq 26$, in order to provide a reasonable level of photometric completeness.

3 Selection of $z \sim 4$ Lyman Break Galaxies

Our catalog contains 42,557 objects with $i' \leq 26.0$ in total. On the basis of expectations from GISSEL96 [4] population synthesis models, we define the photometric selection criteria for galaxies at $z \sim 4$ (13 for model parameters) as

$$B - R > 2.1, R - i' < 0.5, B - R > 5.4(R - i') + 0.9$$  (1)

We estimate the redshift distribution, $N(z)$, of galaxies satisfying equation (1) from the HDF-N objects for which magnitudes, colors, and photometric redshifts are given in [5]. We find that the criteria select $z = 3.8 \pm 0.5$ galaxies. There are a total of 1192 objects that meet the criteria. Figure 1 shows the $B - R$ vs. $R - i'$ color diagram for model galaxies and Gunn & Stryker’s stars [4] (left panel), and for 5$\sigma$ detected objects in our data (right panel). The left panel demonstrates that $z \sim 4$ galaxies are well isolated from interlopers, i.e., low-$z$ galaxies and Galactic stars. We have estimated the contamination and completeness of our LBG sample by Monte Carlo simulations, generating artificial objects which mimic the HDF-N galaxies and distributing them on our original images. The contamination is defined, for the detected simulated objects, as the ratio of low-redshift ($z < 3.3$) objects meeting equation (1) to all the objects satisfying equation (1). The completeness is defined as the ratio of $z \sim 4$ simulated objects passing our detection threshold and satisfying equation (1) to all (detected + undetected) $z \sim 4$ simulated objects. We find from the simulations that the completeness and the contamination are 45% and 17%, respectively.
Figure 2: (a) Luminosity function (LF) of \( z \sim 4 \) LBGs, together with those for \( z = 0 \) and 3 galaxies. The filled circles indicate \( z \sim 4 \) LBGs derived from our data, and the squares are for the \( z \sim 4 \) galaxies from the HDF photo-z catalog \([5]\). The solid line shows the best fitted Schechter function to the \( z \sim 4 \) data. The dashed line is the LF of UV selected galaxies at \( z = 0 \) (whose magnitudes are \( M_{AB}^{(2000\AA)} \) \([22]\)). The dotted line denotes the LF of \( z \sim 3 \) LBGs \([21]\). A large population of UV-luminous (\( M_{AB} < -20 \)) galaxies is seen at \( z \sim 3 \) and 4. (b) LFs of the red and blue subsamples. The filled circles and filled squares show the red sample, while the open circles and open squares are for the blue sample. The solid line is the best fitted Schechter function obtained from the whole sample, which is shown as the solid line in (a). See text for details.

4 Luminosity Function

The UV luminosity function (LF) of \( z \sim 4 \) LBGs is derived from our 1192 objects with \( i' < 26 \). We calculate the surveyed effective volume which is the integrated volume from \( z = 3.3 \) to \( z = 4.3 \) by taking into account the completeness and contamination of the sample selection, and \( N(z) \) \([5]\). The LF is shown in figure 3(a), together with those at \( z = 0 \) \([22]\) and \( z \sim 3 \) \([21]\). The LF of our \( z \sim 4 \) LBG sample is consistent with the one derived by \([21]\). We fit the Schechter function to the LF, and find \( M_{AB}^{(1700\AA)} = -20.41, \phi^* = 1.9 \times 10^{-3} \) with a fixed slope \( \alpha = -1.6 \). It is found from figure 2(a), that all the LFs from \( z=0 \) to 4 seem to prefer a steep slope, \( \alpha \simeq -1.6 \). The \( M^* \)s at \( z \sim 3 \) and 4 are about 2 magnitude brighter than that at \( z=0 \). The number of bright (\( M_{AB}^{(1700\AA)} \lesssim -20 \)) galaxies are much larger at high redshifts than in the local universe, while that of faint galaxies are comparable. This implies that a large population of UV-luminous galaxies exists only at high redshifts. This population reflects the high cosmic starformation rates at high redshifts, which were derived by \([10]\) and \([21]\). There are two extreme explanations for this population. One is that the star-formation rate of \( z \sim 3 - 4 \) galaxies is intrinsically higher than that for \( z = 0 \) galaxies, and the other is that the \( z \sim 3 - 4 \) galaxies are very dust-poor (or partially dust free) and thus the \( M^* \) values are apparently brighter than that for \( z = 0 \) galaxies which suffer from non-negligible dust extinction. A detailed discussion will be given in \([14]\).

We divide our whole LBG sample into two subsamples, blue and red, by the \( R - i' \) color. The blue (red) sample is composed of objects bluer (redder) than the median color of the whole sample, \(<R - i' > 0.12 \). The LFs of red and blue samples are calculated in the same manner as for the whole sample. Figure 2(b) shows the LFs of red and blue samples. These LFs are not significantly different at the faint end (\( M_{AB} > -20.3 \)), however, the LF of red sample seems to be higher than that of the blue sample at the bright end (\( M_{AB} < -20.3 \)). This may imply that the bright LBGs are dominated by galaxies red in the \( R - i' \) color. The \( R - i \) color reflects the shape of UV continuum between \( 1380 - 1620\AA \) for \( z = 3.8 \) LBGs \([4]\) and the difference in the color is thought to be caused by various 1530\AA - 1810\AA \) for \( z = 3.3 \) LBGs, 1250\AA - 1470\AA \) for \( z = 4.3 \) LBGs.
Figure 3: (a) Sky distribution of the $z \sim 4$ LBGs. Different symbols correspond to different magnitude bins defined in the panel. Masked regions, to avoid the effects of bright stars, are shown as dotted circles. (b) Angular correlation function for the $z \sim 4$ LBGs. The solid line shows the best-fit power law with $\omega(\theta) = A_\omega \theta^{-\beta}$.

reasons, for example, differences in dust extinction, stellar population, and redshift. If the difference in the color is mainly originated from the dust extinction, the boundary of the color, $R - i = 0.12$, is estimated to be $E(B - V) \simeq 0.18$, following [11]. If this is the case, the brighter LBGs may be dominated by dusty LBGs with $E(B - V) > 0.18$. Note that in deriving the red and blue LFs, we assume that the completeness and the contamination of these subsamples are the same as for the whole sample. We should point out the possibility that the difference in red and blue LFs comes from a systematic difference in the completeness and contamination factors of the blue and red samples.

5 Angular Correlation Function

Figure 3(a) shows the sky distribution of $z \sim 4$ LBGs in our sample. In this figure, we find a somewhat inhomogeneous distribution of LBGs, especially for bright ($i' < 24.5$) ones. We derive the angular two-point correlation function $\omega(\theta)$ using the estimator defined by [9] (see [13]). The resulting angular correlation function for the sample is shown in figure 3(b)².

We fit a power law, $\omega(\theta) = A_\omega \theta^{-\beta}$, to the data points, and find the slope $\beta = 0.6^{+0.6}_{-0.4}$, which is consistent with those for nearby galaxies, $\beta = 0.7 - 0.8$, though the errors in our estimate are large. The best fit value for $\beta \equiv 0.8$ is $A_\omega = 0.71 \pm 0.26$ in units of arcsec$^2$.

The two-point angular correlation function is related to the spatial correlation function $\xi(r) = (r/r_0)^{-\gamma}$ by an integral equation, the Limber transformation [17]. We apply the Limber transformation to the best fit value of $A_\omega$ with $\beta \equiv 0.8$, using the redshift distribution $N(z)$ of the LBGs ([3]). The obtained correlation length is $r_0 = 2.7^{+0.9}_{-0.7} h^{-1} \text{Mpc}$. This is twice as large as the correlation length of the dark matter at $z \simeq 4$ predicted from an analytic model by [16]. The difference is thought to be due to the biasing of galaxy distribution, which is characterized by the biasing factor, $b$, as $\xi_{\text{gal}}(r) = b^2 \xi_{\text{matter}}(r)$. We obtain a linear bias $b \simeq 2.6$, which is similar to that found by [1] for bright $z \simeq 3$ LBGs. On the other hand, the semianalytic models predict much stronger clustering for galaxies ([1], [8]). A further discussion requires a detailed comparison of galaxy properties and selection criteria, between galaxies in the models and LBGs in our sample.

In figure 3(b), we find an excess ³ of $\omega(\theta)$ at small scales ($\theta \lesssim 5''$) at $> 3\sigma$ significance levels.

²Error bars do not include sample variance caused from field-to-field variations. The effect of the variations in our sample is probably modest since our sample probes a large comoving volume, $36 \times 36 \times 520 = 6.7 \times 10^5 h^{-1} \text{Mpc}^3$.

³With a visual inspection, we find that all the galaxies contributing to the excess are real; no artificial objects, such as halos of bright stars, are found to be included in them.
relative to the best-fit power law. This can be caused by various effects; for example, galaxy-galaxy mergers, two galaxies within a common dark matter halo, and/or field variance. If we interpret this as galaxy-galaxy mergers of those \( i' < 26 \) LBGs, which are classified as bright LBGs with \( M_{1700\AA} \lesssim M^*_{1700\AA} \) (\[4\]), we can calculate, following \[19\], the fraction of galaxies undergoing mergers as from the observed and expected numbers of galaxy pairs with a separation of \( 1.5'' < \theta < 4'' \) (the projected physical separation corresponds to 7.5 to 20 \( h^{-1}\text{kpc} \) at \( z = 3.8 \)). The resulting value is \( f_{\text{pair}} = 3.0 \pm 0.9\% \). This value is significantly smaller than those for intermediate-redshift (\( z \sim 0.3 \)) galaxies whose \( f_{\text{pair}} \) at \( \lesssim 20 \ h^{-1}\text{kpc} \) is 5 – 15\% (e.g. \[19\]).

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