THE SPACE DENSITY AND COLORS OF MASSIVE GALAXIES AT 2 < Z < 3: THE PREDOMINANCE OF DISTANT RED GALAXIES

P. G. van Dokkum1, R. Quadri2, D. Marchesini1, G. Rudnick2, M. Franx3, E. Gawiser1,4, D. Herrera4, S. Wuyts3, P. Lira5, I. Labbé5,6, J. Maza6, G. D. Illingworth7, N. M. Förster Schreiber8, M. Kriek4, H.-W. Rix9, E. N. Taylor1, S. Toft1, T. Webb3, and S. K. Yi10

Accepted for publication in Astrophysical Journal Letters

ABSTRACT

Using the deep multi-wavelength MUSYC, GOODS, and FIRES surveys we construct a stellar mass-limited sample of galaxies at 2 < z < 3. The sample comprises 294 galaxies with M > 10^{11} M_⊙ distributed over four independent fields with a total area of almost 400 arcmin^2. The mean number density of massive galaxies in this redshift range \( \rho(M > 10^{11} M_⊙) = (2.2 \pm 0.6) \times 10^{-4} h^3_{70} \text{ Mpc}^{-3} \). We present median values and 25th and 75th percentiles for the distributions of observed \( R_{AB} \) magnitudes, observed \( J - K_s \) colors, and rest-frame ultra-violet continuum slopes, \( M/L_V \) ratios, and \( U - V \) colors. The galaxies show a large range in all these properties. The “median galaxy” is faint in the observer’s optical (\( R_{AB} = 25.9 \)), red in the observed near-IR (\( J - K_s = 2.48 \)), has a rest-frame UV spectrum which is relatively flat in \( F_\lambda (\beta = -0.4) \), and rest-frame optical colors resembling those of nearby spiral galaxies (\( U - V = 0.62 \)). We determine which galaxies would be selected as Lyman break galaxies (LBGs) or Distant Red Galaxies (DRGs, having \( J - K_s > 2.3 \)) in this mass-limited sample. By number DRGs make up 69% of the sample and LBGs 20%, with a small amount of overlap. By mass DRGs make up 77% and LBGs 17%. Neither technique provides a representative sample of massive galaxies at 2 < z < 3 as they only sample the extremes of the population. As we show here, multi-wavelength surveys with high quality photometry are essential for an unbiased census of massive galaxies in the early Universe. The main uncertainty in this analysis is our reliance on photometric redshifts; confirmation of the results presented here requires extensive near-infrared spectroscopy of optically-faint samples.

Subject headings: cosmology: observations — galaxies: evolution — galaxies: formation

1. INTRODUCTION

The properties of massive galaxies at high redshift place important constraints on galaxy formation models (see, e.g., Kauffmann & Charlot 1998; Nagamine et al. 2005). The “standard” and most successful method for finding distant galaxies is the Lyman dropout technique, which relies on the strong break in the rest-frame ultra-violet (UV) spectra of high redshift galaxies blueward of the Lyman limit (Steidel et al. 1996, 1999). However, it is not yet clear whether these galaxies are representative of the high redshift galaxy population, in particular at the high-mass end. As the Lyman break selection requires that galaxies are very bright in the rest-frame UV it may miss objects that are heavily obscured by dust or whose light is dominated by evolved stellar populations.

Advances in instrumentation have made it possible to select galaxies in complementary ways, and recent studies have demonstrated that the universe at z > 2 is much more diverse than had been realized. Among recently identified “new” galaxy populations are submm galaxies (e.g., Smail et al. 2004), distant red galaxies (DRGs) selected by the criterion \( J - K_s > 2.3 \) (Franx et al. 2003; van Dokkum et al. 2003), “IRAC Extremely Red Objects” (IEROs; Yan et al. 2004), and “BzK” objects (Daddi et al. 2004).

The current situation is somewhat confusing, as the relative contributions of the various newly identified galaxy populations to the stellar mass budget and the cosmic star formation rate are still unclear. Furthermore, as emphasized by, e.g., Adelberger et al. (2005) and Reddy et al. (2005), there can be considerable overlap between selection techniques, which makes it difficult to interpret the plethora of windows on the high redshift Universe.

Ideally samples of high redshift galaxies are selected not by color or luminosity but by stellar mass. Whereas luminosities and colors can vary dramatically due to star bursts and the presence of dust the mass evolution of galaxies is probably gradual. Also, galaxy formation models can predict masses with somewhat higher confidence than luminosities and colors. Stellar masses of distant galaxies are usually determined by fitting stellar population synthesis models to broad band photometry. Although there are significant systematic uncertainties, the stellar mass of a galaxy is usually better constrained than the instantaneous star formation rate, age, or dust content (e.g., Shapley et al. 2001; Papovich et al. 2001; van Dokkum et al. 2004; Förster Schreiber et al. 2004).

In this Letter we explore the properties of a stellar-mass limited sample of galaxies. The main purpose is to measure “basic” aspects of massive galaxies to compare with simulations of galaxy formation: their density and colors. A secondary goal is to quantify selection biases introduced by two of the most widely used techniques for identifying distant galaxies: the Lyman break technique and the \( J - K \) color selection of Franx et al. (2003). We assume \( \Omega_m = 0.3, \Omega_\Lambda = 0.7, \)
parameterized by a declining star formation rate with char-
acteristic timescale $\tau \approx 0.3$ Gyr (see Förster Schreiber et al. 2004). The Calzetti (1997) reddening law was used, with extinction ranging from $A_{V} = 0$ to $A_{V} = 3$. We note that the derived masses are probably not significantly affected by the presence of AGN (e.g., Rubin et al. 2004, Reddy et al. 2005), as their contributions to the broad band fluxes are probably small (Förster Schreiber et al. 2004; Webb et al. 2006).

First, we compared the masses derived from $U-K_{s}$ photometry to masses derived from $U-K_{s}$ plus Spitzer/IRAC photometry in the HDF-S (Labbe et al. 2005). Although the masses of individual galaxies can vary by $\sim 30\%$ the systematic difference is $\leq 10\%$. Next, we determined what fraction of massive galaxies are fainter than $K_{s} = 21.3$, the approximate limit of the MUSYC survey. Only 5% of galaxies with $M > 10^{11} M_{\odot}$ in the deep FIRES and GOODS fields have $K_{s} > 21.3$. Extremely obscured massive galaxies could be missed even in the deep FIRES and GOODS data, but the fact that $\sim 90\%$ of submm-selected galaxies at $z \sim 2.2$ have $K < 21$ (Smail et al. 2004) implies that such objects are very rare. We conclude that our mass-limited sample of 294 galaxies at $2 < z < 3$ is $\sim 95\%$ complete.

3. DENSITY

The FIREs, GOODS, and MUSYC surveys cover four independent fields: FIREs MS 1054–03 (23 arcmin$^{2}$), GOODS CDFS$^{11}$ (69 arcmin$^{2}$), MUSYC SDSS 1030 (103 arcmin$^{2}$), and MUSYC HDFS (188 arcmin$^{2}$). The total area is 383 arcmin$^{2}$, of which 76% is contributed by MUSYC. The average surface density of $M > 10^{11} M_{\odot}$ galaxies with $2 < z < 3$ is 0.71 arcmin$^{-2}$, but there are large field-to-field variations. The density in the CDFS field is only 0.42 arcmin$^{-2}$, 60% of the mean and a factor of three lower than that of the highest density field, SDSS 1030. This large variation is indicative of strong clustering and implies that densities inferred from individual $\sim 100$ arcmin$^{2}$ fields should be treated with caution.

After a 5% correction for incompleteness the mean space density $\rho(M > 10^{11} M_{\odot}) = (2.2 \pm 0.6) \times 10^{-4}$ Mpc$^{-3}$. The uncertainty includes the effects of field-to-field variations, but does not include possible effects caused by systematic errors in the photometric redshifts (see, e.g., Shapley et al. 2005). We note that this density is a factor of $\sim 5$ lower than that of $z \approx 3$ U-dropout galaxies to $R_{AB} = 25.5$ (Steidel et al. 1999), which typically have much lower masses.

4. PROPERTIES OF MASSIVE GALAXIES AT $2 < Z < 3$

We use our mass-limited sample of 294 galaxies to determine the median and dispersion in observed and rest-frame properties of the galaxies. Table 1 gives the median and 25/75-percentiles of the distributions of observed $R_{AB}$ magnitude and $J-K_{s}$ color; rest-frame $U-V$ color and $M/L_{V}$ ratio; and rest-frame UV slope, parameterized by $F_{3} \propto \lambda^{\beta}$. The rest-frame $V$ magnitudes and $U-V$ colors were determined from the observed magnitudes following similar procedures as those outlined in van Dokkum & Franx (1996). Rest-UV slopes $\beta$ were determined from the best fitting spectral energy distributions (SEDs), following the Calzetti, Kinney, & Storchi-Bergmann (1994) method of fitting to the ten rest-UV bins defined by those authors.

As can be inferred from Table 1 the galaxies span a large range in all these properties. The “median galaxy” is red and faint in the observer’s optical, with $R_{AB} = 25.9$. We show the full distribution of the rest-frame $U-V$ colors in Fig. 2(a). The bluest galaxies have $U-V < -0.1$ and are bluer.

\footnote{Area with $JHK_{s}$ coverage.}
distribution is rather flat and has no well-defined peak, in contrast to previous studies of optically-selected samples (Adelberger & Steidel 2000). The median $\langle \beta \rangle = -0.39$, indicating a relatively flat spectrum in $F_{\lambda}$. A potential worry is that individual values of $\beta$ are uncertain, as many galaxies are very faint in the observer’s optical. We tested the robustness of the derived distribution of $\beta$ by summing the observed optical fluxes of the galaxies in the lower and upper 25% quartiles, weighting by the inverse of the total optical flux. The power-law slopes of these summed SEDs are in very good agreement with the median $\beta$ that we determined from the SED fits.

The large range of properties of massive galaxies at $2 < z < 3$ is illustrated in Fig. 4 which shows the full $UBVRi'zJHK_s$ SEDs of three galaxies from the MUSYC survey with different values of $\beta$. The top galaxy has a very blue SED similar to those of UV-selected samples (see, e.g., Shapley et al. 2001), the middle object has an SED that resembles that of nearby spiral galaxies, and the bottom galaxy has a very red SED indicating strong extinction.

The large variation in the rest-frame color distributions of our mass-limited sample implies that “standard” color selection techniques produce biased samples. We consider two of the two most widely used selection techniques in this redshift range: the Lyman break technique of Steidel and collaborators and the $J-K_s > 2.3$ Distant Red Galaxy (DRG) selection (Franx et al. 2003; van Dokkum et al. 2003). Lyman break galaxies are identified in the following way. From the best-fitting Bruzual & Charlot (2003) SEDs (which include absorption due to the Ly α forest) we calculated synthetic colors in Steidel’s $U_vGR$ system. To qualify as an LBG an object has to have $R_{AB} < 25.5$ and synthetic $U_vGR$ colors which place it in the Lyman break, BX, or BM selection region (see Steidel et al. 2003, 2004). Combined these criteria provide a continuous selection of galaxies over the redshift range considered here.12 Figure 4 illustrates the LBG and DRG selection techniques, as applied to our sample. DRGs with $J-K_s > 2.3$ are indicated by red symbols and LBGs by blue symbols. The DRG limit and the “standard” photometric LBG limit of $R_{AB} = 25.5$ are also indicated.13

5. DISCUSSION

The main result of our analysis is that massive galaxies at $z \sim 2.5$ span a large range in rest-frame UV slopes, rest-frame optical colors, and rest-frame $M/L_V$ ratios, indicating significant variation in dust content, star formation histories, or both. This result is not surprising in the light of the recent discoveries of DRGs, IEROs, and other populations. Here we have quantified the median colors and their range for a uniformly selected, large, mass-limited sample.

The large variation in the rest-frame color distributions of our mass-limited sample implies that “standard” color selection techniques produce biased samples. We consider two of the two most widely used selection techniques in this redshift range: the Lyman break technique of Steidel and collaborators and the $J-K_s > 2.3$ Distant Red Galaxy (DRG) selection (Franx et al. 2003; van Dokkum et al. 2003). Lyman break galaxies are identified in the following way. From the best-fitting Bruzual & Charlot (2003) SEDs (which include absorption due to the Ly α forest) we calculated synthetic colors in Steidel’s $U_vGR$ system. To qualify as an LBG an object has to have $R_{AB} < 25.5$ and synthetic $U_vGR$ colors which place it in the Lyman break, BX, or BM selection region (see Steidel et al. 2003, 2004). Combined these criteria provide a continuous selection of galaxies over the redshift range considered here.12 Figure 4 illustrates the LBG and DRG selection techniques, as applied to our sample. DRGs with $J-K_s > 2.3$ are indicated by red symbols and LBGs by blue symbols. The DRG limit and the “standard” photometric LBG limit of $R_{AB} = 25.5$ are also indicated.13

12 A LBG in this definition is therefore an object which has $R_{AB} < 25.5$, $2 < z_{\text{phot}} < 3$, and is either a classical “U-dropout” or a BX/BM object.
13 We note that not all galaxies with $J-K_s > 2.3$ have redshifts in the range $2 < z < 3$, to $K_s = 21$ we find that $\sim 50\%$ are in this redshift range with the rest about equally split between $z < 2$ and $z > 3$ galaxies.
denote DRGs with blue near-IR colors and are bright in the observed R band. The inset shows the optical color distribution of galaxies with $R < 25.5$. Only ∼ 50% of optically-bright massive galaxies have the colors of LBGs.

By number, DRGs make up 69% of the sample and LBGs 20%. The DRG and LBG samples do not show much overlap: only 7% of objects fall in both categories. By rest-frame V-band luminosity DRGs contribute 64% and LBGs 32%. By mass DRGs contribute 77% and LBGs 17%. Together, the LBG and DRG techniques identify 82% of massive galaxies by number and 84% by mass. Most of the remaining galaxies are optically faint, slightly bluer than the $J - K_s = 2.3$ limit, and have redshifts $z < 2.5$. Approximately 85% of them fall in the “BzK” selection region (Daddi et al. 2004), which is optimized for galaxies at $1.4 < z < 2.5$. We note that the relatively small fraction of LBGs in the sample is not solely due to the imposed $R_{AB} < 25.5$ limit. As shown in the inset of Fig. 4, only ∼ 50% of galaxies with $R_{AB} < 25.5$ have the rest-UV colors of LBGs, and this fraction decreases going to fainter $R$ magnitudes: when no $R$ limit is imposed we find that ∼ 1/3 of the galaxies have the colors of LBGs. The underlying reason is the broad distribution of $\beta$.

It is clear from Fig. 4 that the LBG selection produces very different samples of massive high redshift galaxies than the DRG selection. Both samples are biased: LBGs are too blue and DRGs are too red when compared to the median values of the full sample. This bias is shown explicitly by the blue and red histograms in Fig. 2. The Lyman break criteria were designed to find star forming galaxies, but Shapley et al. (2004) and Adelberger et al. (2005) have argued that they can also be used to find massive galaxies at high redshift. This is obviously the case, but we find that the colors and $M/L_V$ ratios of massive LBGs are not representative for the full sample of massive galaxies. Surveys over the full set of optical/near-IR passbands from $U$ through $K$ are essential to obtain representative samples of massive galaxies.

The main uncertainty in this analysis is the reliance on photometric redshifts. We estimated the effect of this uncertainty by randomly perturbing the redshifts using a Gaussian distribution with dispersion $\Delta z/(1+z) = 0.12$, and repeating the selection and analysis. Despite significant migration of galaxies in and out of the $2 < z < 3$ redshift range the values in Table 1 change by only ∼ 10%. We note, however, that there may be subtle systematic biases which can have significant effects, in particular on the derived masses (see, e.g., Shapley et al. 2005). Comprehensive tests of the techniques employed here and in other studies of infra-red selected samples (e.g., Dickinson et al. 2003, Rudnick et al. 2003) are urgently needed, and will become feasible with the introduction of multi-object near-IR spectrographs on 8m class telescopes.

We thank the anonymous referee for insightful comments which improved the manuscript significantly. PGVD acknowledges support from NSF CAREER AST-0449678. DM is supported by NASA LTSA NNG04GE12G. EG is supported by NSF Fellowship AST-0201667. ST is partly supported by the Danish Natural Research Council.

REFERENCES

Adelberger, K. L., Erb, D. K., Steidel, C. C., Reddy, N. A., Pettini, M., & Shapley, A. E. 2005, ApJ, 620, L75
Adelberger, K. L. & Steidel, C. C. 2000, ApJ, 544, 218
Armus, L., Heckman, T. M., & Miley, G. K. 1989, ApJ, 347, 727
Bruzual, G. & Charlot, S. 2003, MNRAS, 344, 1000
Calzetti, D. 1997, AJ, 113, 162
Calzetti, D., Kinney, A. L., & Storchi-Bergmann, T. 1994, ApJ, 429, 582
Daddi, E., Civano, F., Renzini, A., Scott, D., Mignoli, M., Pozzetti, L., Tozzi, P., & Zammorini, G. 2004, ApJ, 617, 746
Dickinson, M., Papovich, C., Ferguson, H. C., & Budavári, T. 2003, ApJ, 587, 25
Förster Schreiber, N. M., et al. 2004, ApJ, 616, 40
Franx, M., et al. 2003, ApJ, 587, L79
Fukugita, M., Shimasaku, K., & Ichikawa, T. 1995, PASP, 107, 945
Gawiser, E., et al. 2006, ApJS, in press
Giavalisco, M., et al. 2003, ApJ, 592, 728
Giavalisco, M., et al. 2004, ApJ, 600, L95
Kauffmann, G. & Charlot, S. 1998, MNRAS, 297, L23
Labbé, I. et al. 2003, AJ, 125, 1107
Labbé, I. et al. 2005, ApJ, 624, L81
Nagamine, K., Cen, R., Hernquist, L., Ostriker, J. P., & Springel, V. 2005, ApJ, 627, 608
Papovich, C., Dickinson, M., & Ferguson, H. C. 2001, ApJ, 559, 620
Reddy, N. A., Erb, D. K., Steidel, C. C., Shapley, A. E., Adelberger, K. L., & Pettini, M. 2005, ApJ, 633, 748
Rubin, K. H. R., et al. 2004, ApJ, 613, L5
Rudnick, G., et al. 2001, AJ, 122, 2205
Rudnick, G., et al. 2003, ApJ, 599, 847
Salpeter, E. E. 1955, ApJ, 121, 161
Shapley, A. E., Erb, D. K., Pettini, M., Steidel, C. C., & Adelberger, K. L. 2004, ApJ, 612, 108
Shapley, A. E., Steidel, C. C., Adelberger, K. L., Dickinson, M., & Giavalisco, M., & Pettini, M. 2001, ApJ, 562, 95
Shapley, A. E., et al. 2005, ApJ, 626, 698
Smail, I., Chapman, S. C., Blain, A. W., & Ivison, R. J. 2004, ApJ, 616, 71
Steidel, C. C., Adelberger, K. L., Giavalisco, M., & Pettini, M. 1999, ApJ, 519, L1
Steidel, C. C., Adelberger, K. L., Shapley, A. E., Pettini, M., Dickinson, M., & Giavalisco, M. 2003, ApJ, 592, 728
Steidel, C. C., Giavalisco, M., Pettini, M., Dickinson, M., & Adelberger, K. L. 1996, ApJ, 462, L17
Steidel, C. C., Shapley, A. E., Pettini, M., Adelberger, K. L., Erb, D. K., Reddy, N. A., & Hunt, M. P. 2004, ApJ, 604, 534
van Dokkum, P. G., et al. 2003, ApJ, 587, L83
van Dokkum, P. G. & Franx, M. 1996, MNRAS, 281, 985
van Dokkum, P. G., et al. 2004, ApJ, 611, 703
Webb, T., et al. 2006, ApJ, 636, L17
Yan, H., et al. 2004, ApJ, 616, 63