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

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ABSTRACT

Using the deep multiwavelength MUSYC, GOODS, and FIRES surveys we construct a stellar mass-limited sample of galaxies at $2 < z < 3$. The sample comprises 294 galaxies with $M > 10^{11}\ M_\odot$ 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 $\rho(M > 10^{11}\ M_\odot) = (2.2 \pm 0.6) \times 10^{-4}\ h_{70}^3$ 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 ultraviolet 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 that is relatively flat in F_λ ($\beta = -0.4$), 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, multiwavelength 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 and 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 ultraviolet (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 submillimeter 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 starbursts 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 they can luminosities and colors. Stellar masses of distant galaxies are usually determined by fitting stellar population synthesis models to broadband 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 $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s^{-1} Mpc^{-1}. All magnitudes are on the Vega system, unless identified as "AB."

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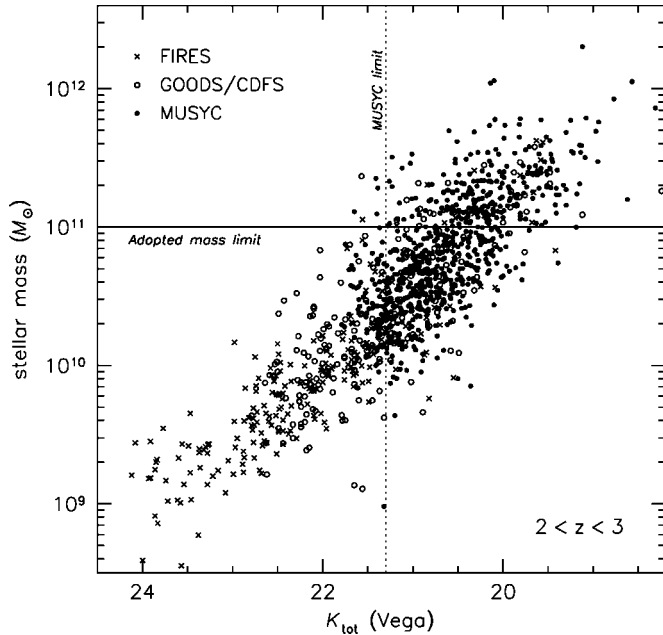FIG. 1.—Relation between stellar mass and observed total K_s magnitude for galaxies at $2 < z_{\rm phot} < 3$. The solid line shows our selection limit of $M > 10^{11}\,M_\odot$. The dotted line shows the approximate photometric limit of MUSYC, which accounts for the majority of galaxies in our sample. There are very few galaxies in FIRES and GOODS with $M > 10^{11}\,M_\odot$ and $K_s > 21.3$, and we estimate that the completeness of the full sample of $M > 10^{11}\,M_\odot$ galaxies is $\approx 95\%$.

2. DEFINITION OF THE SAMPLE

The sample is drawn from three deep multiwavelength surveys, all having high-quality optical–near-IR photometry: the "ultra-deep" Faint InfraRed Extagalactic Survey (FIRES; Franx et al. 2003), the Great Observatories Origins Deep Survey (GOODS; Giavalisco et al. 2004) Chandra Deep Field–South (CDF-S), and the new Multiwavelength Survey by Yale-Chile (MUSYC; Gawiser et al. 2005; R. Quadri et al. 2006, in preparation).

Photometric catalogs were created for all fields in the same way, following the procedures of Labbé et al. (2003). Photometric redshifts were determined using the method of Rudnick et al. (2001, 2003). Comparing the photometric redshifts with 696 spectroscopic redshifts (63 at $z \geq 1.5$) gives a scatter in $\Delta z/(1 + z)$ of $\sigma = 0.06$. Restricting the analysis to galaxies at $z \geq 1.5$ in the MUSYC fields gives $\sigma = 0.12$, corresponding to $\Delta z \approx 0.4$ at $z = 2.5$. Approximately 5% of galaxies in this sample are "catastrophic" outliers. A full discussion of the quality of the photometric redshifts is given elsewhere (G. Rudnick et al. 2006, in preparation). To determine masses, stellar population synthesis models were fit to the photometry using standard techniques (see, e.g., Sawicki & Yee 1998 and Förster Schreiber et al. 2004). Bruzual & Charlot (2003) models were used, with solar metallicity (Shapley et al. 2004; van Dokkum et al. 2004) and a Salpeter (1955) initial mass function from 0.1 to 100 $M_\odot$. Star formation histories were parameterized by a declining star formation rate with a characteristic timescale $\tau = 0.3$ 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 active galactic nuclei (e.g., Rubin et al. 2004; Reddy et al. 2005), as their contributions to the broadband fluxes are probably small (Förster Schreiber et al. 2004; Webb et al. 2006).

Figure 1 shows the relation between stellar mass and observed total K_s magnitude for galaxies with photometric redshifts $2 <$

Quantity	25%	Median	75%
$R_{\rm tot,\,AB}$ (obs)	25.1	25.9	26.7
$J - K_s$ (obs)	2.22	2.48	2.85
$U - V$ (rest)	0.41	0.62	0.80
$\log (M/L_V)$ (rest)	0.05	0.20	0.30
β (rest)	-1.13	-0.39	0.31

$z < 3$. There is a clear relation, with a scatter of a factor of ~10. We selected all 294 galaxies with $2 < z_{\rm phot} < 3$ and stellar masses $M > 10^{11}\,M_\odot$ in the three surveys. The reliability of this procedure was assessed in the following ways. First, we compared the masses derived from $U - K_s$ photometry to masses derived from $U - K_s$ plus *Spitzer*/IRAC photometry in the Hubble Deep Field–South (HDFS; Labbé et al. 2005). Although the masses of individual galaxies can vary by ~30%, the systematic difference is $\lesssim 10\%$. Next, we determined what fraction of massive galaxies are fainter than $K_s = 21.3$, the approximate limit of MUSYC. 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 ~90% of submillimeter-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 ~95% complete.

3. DENSITY

The FIRES, GOODS, and MUSYC surveys cover four independent fields: FIRES MS $1054-03$ (23 arcmin^2), GOODS CDF-S[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 CDF-S field is only 0.42 arcmin^{-2}, 60% of the mean and a factor of 3 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 ~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 ~5 lower than that of $z \approx 3$ U-dropout galaxies to $R_{\rm AB} = 25.5$ (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 25th/75th percentiles of the distributions of observed $R_{\rm AB}$ magnitude and $J - K_s$ color; rest-frame $U - V$ color and M/L_V ratio; and rest-frame UV slopes, parameterized by $F_\lambda \propto \lambda^\beta$. 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-frame UV slopes β were determined from the best-fitting spectral energy distri-
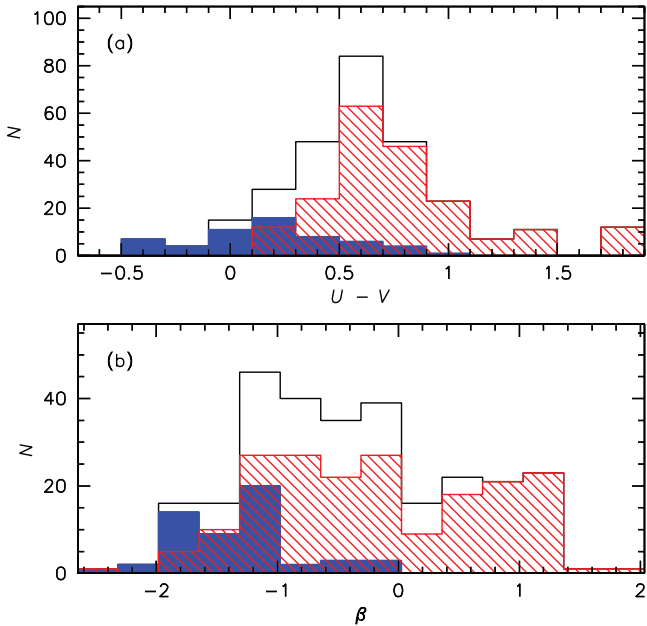
[11] Area with JHK_s coverage.

Fig. 2.—Distribution of rest-frame $U - V$ colors (*a*) and rest-frame UV slope β (*b*) for galaxies with $M > 10^{11}\ M_\odot$ and $2 < z_{phot} < 3$. The galaxies show a wide range in rest-frame optical and rest-frame UV colors. Blue histograms indicate galaxies with the colors and luminosities of LBGs; red histograms indicate DRGs.

Fig. 3.—SEDs of three MUSYC galaxies with different rest-frame UV slope β. Overplotted are the best-fitting Bruzual & Charlot (2003) models. From top to bottom, the galaxies have $\beta = -1.3$, -0.2, and 0.9 respectively. The blue rest-frame UV SED of the top object is typical for LBGs. The slope of the middle galaxy is close to the median value of the full sample.

butions (SEDs), following the Calzetti et al. (1994) method of fitting to the 10 rest-frame 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 $\langle R_{AB}\rangle = 25.9$. We show the full distribution of the rest-frame $U - V$ colors in Figure 2*a*. The bluest galaxies have $U - V < -0.1$ and are bluer than nearby irregular galaxies, whereas the colors of the reddest galaxies are similar to those of nearby elliptical galaxies (see, e.g., Fukugita et al. 1995). The median $\langle U - V\rangle = 0.6$, which is similar to nearby spiral galaxies but also to nearby dust-enshrouded starburst galaxies (e.g., Armus et al. 1989).

The distribution of β is shown in Figure 2*b*. Remarkably, the 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_λ (see also Papovich et al. 2005). A potential worry is that individual values of β are uncertain, as many galaxies are very faint in the observer's optical. We tested the robustness of the derived distribution of β 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 β's that we determined from the SED fits.

The large range of properties of massive galaxies at $2 < z < 3$ is illustrated in Figure 3, which shows the full *UBVRIzJHK$_s$* SEDs of three galaxies from MUSYC with different values of β. 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.

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
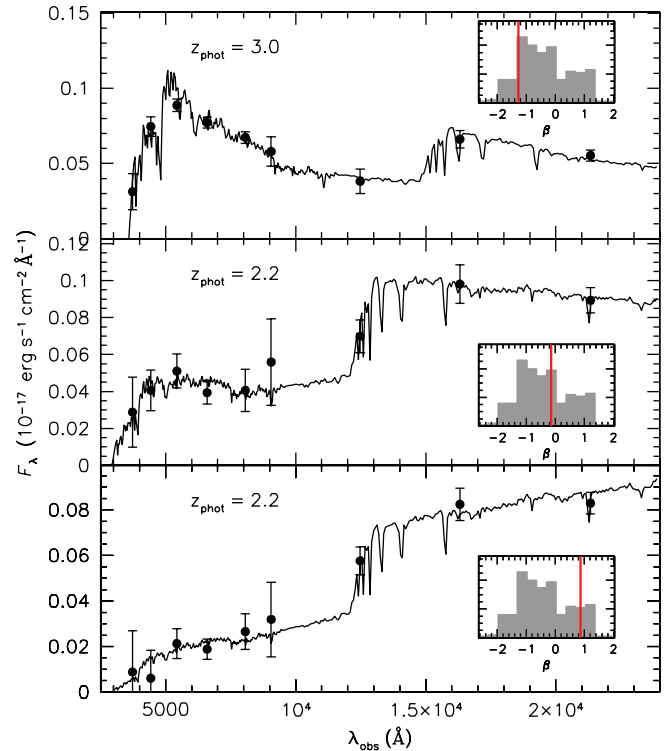
optical colors, and rest-frame M/L_V ratios, indicating significant variation in dust content, star formation histories, or both. This result is not surprising in the light of the recent discoveries of DRGs, IEROs, and other populations. Here we have quantified the median colors and their range for a 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 $J - K_s > 2.3$ DRG selection of Franx et al. (2003). LBGs are identified in the following way. From the best-fitting Bruzual & Charlot (2003) SEDs (which include absorption due to the Lyα forest), we calculated synthetic colors in Steidel's $U_nG\mathcal{R}$ system. To qualify as an LBG, an object has to have $R_{AB} < 25.5$ and synthetic $U_nG\mathcal{R}$ colors that 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]

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-

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[12] An LBG in this definition is therefore an object that has $R_{AB} < 25.5$, $2 < z_{phot} < 3$, 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 ~50% are in this redshift range, with the rest about equally split between $z < 2$ and $z > 3$ galaxies.
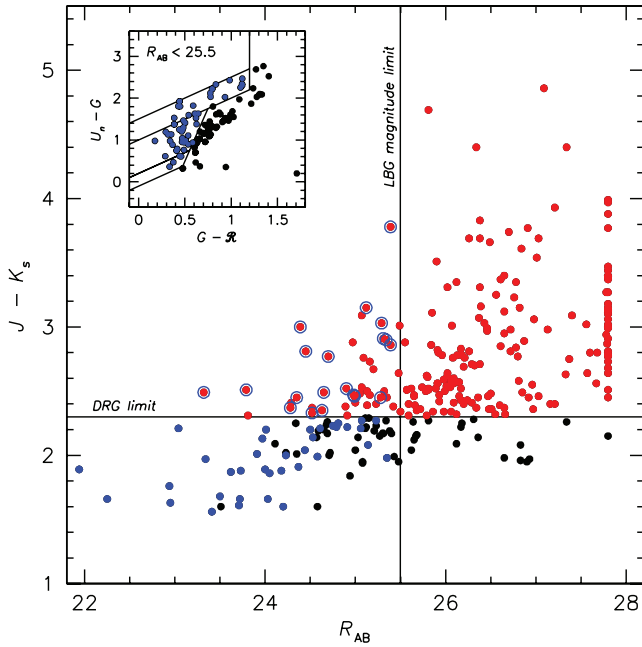
FIG. 4.—Correlation between observed $J - K_s$ color and R_{AB} magnitude. The majority of the galaxies are faint in R and red in $J - K_s$. Red symbols denote DRGs with $J - K_s > 2.3$; blue circles denote LBGs with $R_{AB} < 25.5$. Red symbols with blue circles fall in both categories. Massive LBGs have 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.

$R_{AB} < 25.5$ limit. As shown in the inset of Figure 4, only ~50% of galaxies with $R_{AB} < 25.5$ have the rest-frame UV colors of LBGs, and this fraction decreases going to fainter R magnitudes: when no R limit is imposed. we find that $\sim \frac{1}{3}$ of the galaxies have the colors of LBGs. The underlying reason is the broad distribution of β.

It is clear from Figure 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 Figure 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 that 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 infrared-selected samples (e.g., Dickinson et al. 2003; Rudnick et al. 2003) are urgently needed and will become feasible with the introduction of multiobject near-IR spectrographs on 8 m–class telescopes.

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

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., Cimatti, A., Renzini, A., Fontana, A., Mignoli, M., Pozzetti, L., Tozzi, P., & Zamorani, G. 2004, ApJ, 617, 746
Dickinson, M., Papovich, C., Ferguson, H. C., & Budávari, 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. 2005, ApJS, in press (astro-ph/0509202)
Giavalisco, M., et al. 2004, ApJ, 600, L93
Kauffmann, G., & Charlot, S. 1998, MNRAS, 297, L23
Labbé, I., et al. 2003, AJ, 125, 1107
———. 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
Papovich, C., et al. 2006, ApJ, in press (astro-ph/0511289)
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
———. 2003, ApJ, 599, 847
Salpeter, E. E. 1955, ApJ, 121, 161
Sawicki, M., & Yee, H. K. C. 1998, AJ, 115, 1329
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., Dickinson, M., & Pettini, M. 1999, ApJ, 519, 1
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., & Franx, M. 1996, MNRAS, 281, 985
van Dokkum, P. G., et al. 2003, ApJ, 587, L83
———. 2004, ApJ, 611, 703
Webb, T., et al. 2006, ApJ, 636, L17
Yan, H., et al. 2004, ApJ, 616, 63