The Astrophysical Journal, 587:L83–L87, 2003 April 20

SPECTROSCOPIC CONFIRMATION OF A SUBSTANTIAL POPULATION OF LUMINOUS RED GALAXIES AT REDSHIFTS $z \gtrsim 2$[1,2]

Pieter G. van Dokkum,[3,4] Natascha M. Förster Schreiber,[5] Marijn Franx,[5] Emanuele Daddi,[6] Garth D. Illingworth,[7] Ivo Labbé,[5] Alan Moorwood,[6] Hans-Walter Rix,[8] Huub Röttgering,[5] Gregory Rudnick,[9] Arjen van der Wel,[5] Paul van der Werf,[5] and Lottie van Starkenburg[5]

Received 2002 December 13; accepted 2003 March 6; published 2003 March 18

ABSTRACT

We confirm spectroscopically the existence of a population of galaxies at $z \gtrsim 2$ with rest-frame optical colors similar to normal nearby galaxies. The galaxies were identified by their red near-infrared colors in deep images obtained with the Infrared Spectrometer and Array Camera on the Very Large Telescope of the field around the foreground cluster MS 1054−03. Redshifts of six galaxies with $J_s - K_s > 2.3$ were measured from optical spectra obtained with the W. M. Keck telescope. Five out of six are in the range $2.43 \leq z \leq 3.52$, demonstrating that the $J_s - K_s$ color selection is quite efficient. The rest-frame ultraviolet spectra of confirmed $z > 2$ galaxies display a range of properties, with two galaxies showing emission lines characteristic of active galactic nuclei, two having Lyα in emission, and one showing interstellar absorption lines only. Their full spectral energy distributions are well described by constant star formation models with ages 1.4–2.6 Gyr, except for one galaxy whose colors indicate a dusty starburst. The confirmed $z > 2$ galaxies are very luminous: their K_s magnitudes are in the range 19.2–19.9, corresponding to rest-frame absolute V magnitudes from −24.8 to −23.2. Assuming that our bright spectroscopic sample is representative for the general population of $J_s - K_s$ selected objects, we find that the surface density of red $z \gtrsim 2$ galaxies is ≈0.9 arcmin^{-2} to $K_s = 21$. The surface density is comparable to that of Lyman break–selected galaxies with $K_s < 21$, when corrections are made for the different redshift distributions of the two samples. Although there will be some overlap between the two populations, most "optical-break" galaxies are too faint in the rest-frame ultraviolet to be selected as Lyman break galaxies. The most straightforward interpretation is that star formation in typical optical-break galaxies started earlier than in typical Lyman break galaxies. Optical-break galaxies may be the oldest and most massive galaxies yet identified at $z > 2$, and they could evolve into early-type galaxies and bulges.

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

1. INTRODUCTION

The identification of star-forming galaxies at $z \gtrsim 3$ by the Lyman break technique has greatly enhanced our understanding of galaxy formation and the star formation history of the universe (Steidel et al. 1996, 1999; Madau et al. 1996). Although other high-redshift galaxy populations have since been identified (e.g., Hu, Cowie, & McMahon 1998; Smail et al. 2000; Barger et al. 2001), Lyman break galaxies (LBGs) dominate the UV luminosity density at high redshift (Steidel et al. 1999) and have been argued to be the progenitors of massive galaxies in groups and clusters (e.g., Baugh et al. 1998).

However, the census of normal galaxies at $z \sim 3$ may still be incomplete because of selection effects. The Lyman break technique requires a high rest-frame far-ultraviolet (UV) luminosity and so will preferentially select relatively unobscured, actively star-forming galaxies. Stellar ages of LBGs are typically $\sim 3 \times 10^8$ yr (Papovich, Dickinson, & Ferguson 2001; Shapley et al. 2001), suggesting that the descendants of galaxies that started forming stars at significantly higher redshift ($z > 4$) may be underrepresented in current surveys (e.g., Ferguson, Dickinson, & Papovich 2002).

As shown in a companion paper (Franx et al. 2003), such "evolved" high-redshift galaxies can be selected effectively in the rest-frame optical, which is redshifted to near-infrared (NIR) wavelengths for $z \gtrsim 2$. The criterion $J_s - K_s > 2.3$ is expected to isolate galaxies with prominent rest-frame optical breaks, caused by the 3625 Å Balmer break or the 4000 Å Ca II H+K break.[10] This "optical-break" selection is complementary to the ultraviolet Lyman break selection. In Franx et al. (2003), we show that optical-break galaxies have a high surface density in the Hubble Deep Field–South (HDF-S), and we derive from photometric redshifts that their volume density is comparable to LBGs. In Daddi et al. (2003), we infer that the population is highly clustered. The main uncertainties in Franx et al. are the lack of spectroscopic redshifts and the small 2′.3 × 2′.3 field.

Here we present spectroscopic observations of a small sample of optical-break galaxies in MS 1054−03, a field with a foreground cluster at $z = 0.83$. The NIR imaging data in this field complement our extremely deep Very Large Telescope (VLT) Infrared Spectrometer and Array Camera (ISAAC) data on the HDF-S (Labbé et al. 2003) and consist of 77.5 hr of J_s, H, and K_s imaging with ISAAC distributed over a 5′.4 ×

[1] Based on service mode observations collected at the European Southern Observatory, Paranal, Chile (ESO progamme 164.O-0612).

[2] Based on observations obtained at the W. M. Keck Observatory, which is operated jointly by the California Institute of Technology and the University of California.

[3] Department of Astronomy, Yale University, P.O. Box 208101, New Haven, CT 06520-8101.

[4] California Institute of Technology, MS 105-24, Pasadena, CA 91125.

[5] Leiden Observatory, P.O. Box 9513, J. H. Oort Building, Niels Bohrweg 2, NL-2300 RA, Leiden, Netherlands.

[6] European Southern Observatory, Karl-Schwarzschild-Strasse 2, D-85748 Garching, Germany.

[7] University of California Observatories/Lick Observatory, Natural Sciences II Annex, University of California at Santa Cruz, Santa Cruz, CA 95064.

[8] Max-Plank-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany.

[9] Max-Plank-Institut für Astrophysik, P.O. Box 1317, Karl-Scharzschild-Strasse 1, D-85741 Garching, Germany.

[10] Magnitudes are on the Vega system, unless stated otherwise.

TABLE 1
J_s-K_s SELECTED GALAXIES WITH REDSHIFTS

Galaxy	K_s	$K_{s,\,corr}$ [a]	J_s-K_s [b]	z	$M_{V,\,rest}$ [c]
596	19.68	19.91	2.35	1.189	...
1671	19.09	19.23	2.65	2.424	−23.7
1195	19.29	19.63	2.30	2.425	−23.9
1458	19.71	19.86	2.25	2.427	−23.2
184	19.29	19.40	2.54	2.705	−24.1
1656	19.59	19.81	2.98	3.525	−24.8

NOTE.—Magnitudes are on the Vega system.
[a] K-band magnitudes corrected for weak lensing amplification by the foreground $z = 0.83$ galaxy cluster (Hoekstra, Franx, & Kuijken 2000).
[b] Colors were recalibrated following the initial spectroscopic selection; errors are ≈0.05 mag.
[c] $H_0 = 65$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

5′.4 square of four pointings (N. M. Förster Schreiber et al. 2003, in preparation). Although not as deep as our HDF-S observations, the ~5 times larger area enables us to make a more robust measurement of the surface density and is well suited for efficient multislit spectroscopy.

2. SPECTROSCOPY

Optical spectroscopy was obtained for galaxies in the MS 1054−03 field on 2002 February 14–17 with the Low Resolution Imaging Spectrograph (Oke et al. 1995) on the W. M. Keck telescope. The sample was not restricted to J_s-K_s selected galaxies but also contained candidate $1<z<2$ galaxies selected by their red $I-H$ color. The sample was limited at $K = 20.7$, with priority given to objects with $I<24.5$. Four multislit masks were designed, with faint objects repeated in several or all masks. The 300 line mm^{-1} grism was used on the blue arm, in combination with the D680 dichroic. On the red arm, we used the 600 line mm^{-1} grating (1 μm blaze) on February 14–15 and the 400 line mm^{-1} grating (8500 Å blaze) on February 16–17. Conditions were photometric, and the seeing ranged from 0″.8 to 1″.5. The exposure time ranged from 7.2 ks for the brightest objects to 72 ks for the faintest.

Redshifts were measured for six out of 11 observed J_s-K_s selected galaxies. Five have redshifts in the range 2.43–3.52, with the remaining galaxy showing a faint emission line that we tentatively identify as [O II] λ3727 at $z = 1.19$ (Table 1). Additionally, redshifts were measured for 12 out of 27 observed galaxies with $I-H>3.0$ and $J_s-K_s<2.3$; they are in the range 1.06–1.87, with mean $\langle z\rangle = 1.40$.

The spectroscopic redshifts confirm that our simple J_s-K_s color cut effectively isolates galaxies at $z>2$, indicating only a small (~20%) contamination by (dusty) galaxies at lower redshifts. A concern is that the five J_s-K_s selected galaxies without redshift are at $z\sim1.5$, since there would be no strong spectral features in the observed wavelength range. The importance of this potential bias can be estimated by comparing the photometric redshifts of galaxies with and without spectroscopic redshift. Photometric redshifts were determined using the publically available HYPERZ code (Bolzonella, Miralles, & Pelló 2000); a full discussion will be given in N M. Förster Schreiber et al. (2003, in preparation). As demonstrated in Figure 1, the photometric and spectroscopic redshifts are in good agreement. The red histogram shows the photometric redshift distribution of the five J_s-K_s selected galaxies without spectroscopic redshift. Two are in the range $1.7<z_{phot}<2$, and three have $z_{phot}>2$. The median is 2.4, similar to the median photometric redshift of galaxies with spectroscopic redshifts (2.6). We conclude that there is no evidence of a strong redshift bias in our spectroscopic sample.

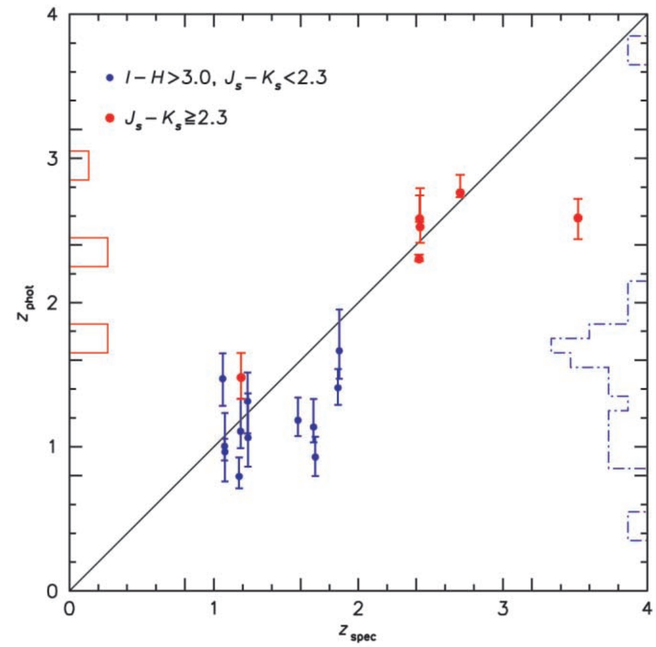

FIG. 1.—Spectroscopic and photometric redshifts of galaxies selected by broadband colors. The 12 galaxies with $I-H>3.0$ and $J_s-K_s<2.3$ have redshifts in the range 1.06–1.87. Five out of six galaxies with $J_s-K_s>2.3$ are at $2.43\le z\le3.52$. The histograms show the photometric redshifts of observed galaxies whose spectra had insufficient signal-to-noise ratios to determine their spectroscopic redshifts.

The redshifts of the five confirmed $z>2$ galaxies span a large range, which is not surprising given the large spacing between the J_s and K_s filters. The mean redshift is 2.7, similar to the median photometric redshift of 2.6 for galaxies with $J_s-K_s>2.3$ and $K_s<22.5$ in the HDF-S (Franx et al. 2003). Remarkably, three galaxies are at almost identical redshift, qualitatively consistent with the strong angular clustering of J_s-K_s selected galaxies in the HDF-S (Daddi et al. 2003).

The J_s-K_s selection is the higher redshift analog of the well-known selection of $1<z<2$ galaxies by their $I-H$ color (e.g., McCarthy et al. 2001), and by combining the two methods, galaxies can be selected over the entire range $1.0\lesssim z\lesssim3.5$ (see Fig. 1). We note that $I-H$ selected galaxies appear to be highly clustered as well: only one out of 12 objects is *not* within 2000 km s^{-1} of another galaxy.

3. SPECTRA OF RED $z>2$ GALAXIES

The rest-frame UV spectra of confirmed $z>2$ galaxies are shown in Figure 2. The small sample displays a wide range of properties: two galaxies have emission lines characteristic of active galactic nuclei (AGNs), two are Lyα emitters with no evidence for the presence of an AGN, and one shows interstellar absorption lines typical of nearby star-forming galaxies.

The high fraction of emission-line galaxies is striking, although in part a selection effect resulting from the difficulty of measuring absorption-line redshifts of these faint galaxies. Our single absorption redshift required an exposure time of 72 ks, and judging from a cross-correlation with an LBG template, it is only marginally significant ($r = 3.1$). Two other

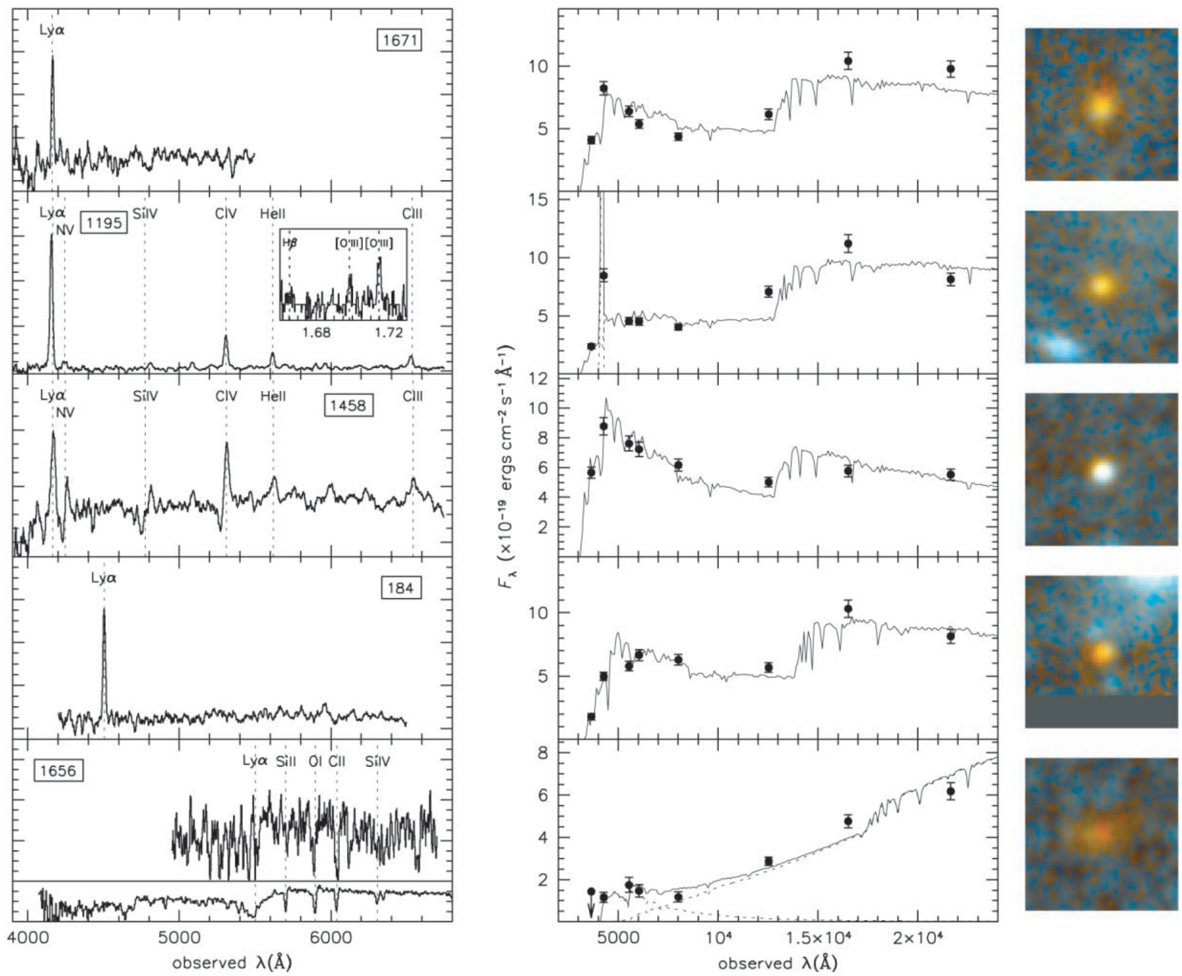

FIG. 2.—*Left panels:* Rest-frame UV spectra of red galaxies at $z > 2$. The spectra display a wide range of properties. The inset for galaxy 1195 shows a NIRSPEC rest-frame optical spectrum. The panel below 1656 shows the mean spectrum of ~250 LBGs without Lyα emission, from Shapley et al. (2003). *Right panels:* SEDs of the same galaxies. Overplotted are models with varying age and dust content (see text). The *B*-, *H*-, and probably J_s-band fluxes of 1195 are affected by strong emission lines. Color images were created from the *HST* $R_{AB} \equiv 0.5(V^{AB}_{F606W} + I^{AB}_{F814W})$ and VLT K_s images (after smoothing to the same resolution) and are 5″.1 × 5″.1.

galaxies show evidence for breaks indicating the onset of the Lyα forest but do not produce significant peaks in their cross-correlation functions. Since there are five observed galaxies without redshift, we estimate that the true emission-line fraction is $\gtrsim$40%. The fact that Lyα photons can escape in some J_s-K_s selected galaxies may indicate that they are not all very dusty or that they have patchy dust distributions.

The two AGNs are at identical redshift and separated by 84″. Galaxy 1195 is a narrow-line AGN similar to type II quasars and nearby Seyfert II galaxies. Galaxy 1458 has a complex spectrum, with narrow (~1500 km s^{-1} FWHM) Lyα and C IV emission lines and broader (~3000 km s^{-1}) He II and C III lines. The resonant transitions N V, Si IV, and C IV show P Cygni profiles, indicative of a radiatively driven ~3000 km s^{-1} wind (e.g., Murray et al. 1995). More data are needed to determine how common AGNs are among J_s-K_s selected galaxies and to compare the rate of occurrence with that in rest-UV–selected objects (Steidel et al. 2002). It is widely believed that all massive, bulge-dominated systems in the local universe harbor massive black holes (e.g., Magorrian et al. 1998), and we can speculate that the optical-break galaxies are progenitors of such galaxies observed at a time when many black holes were still in the process of formation.

4. SPECTRAL ENERGY DISTRIBUTIONS

Broadband spectral energy distributions (SEDs) are shown in the middle panels of Figure 2. Optical data were obtained with the *Hubble Space Telescope* (*HST*) WFPC2 (van Dokkum et al. 2000) and the VLT+FORS; a full description of the photometry is given in N. M. Förster Schreiber et al. (2003, in preparation). We fitted GISSEL98 model spectra from G. Bruzual & S. Charlot (2003, in preparation) in order to interpret the SEDs. As is well known, it is difficult to obtain unique solutions for the functional form of the star formation history, the age of the stellar population, and the dust content (see, e.g., Papovich et al. 2001 and Shapley et al. 2001). Here we only consider models with a constant star formation rate and a Calzetti et al. (2000) reddening law.

As shown in Figure 2, the two Lyα-emitting galaxies 1671 and 184 are fairly well fitted by such models. The same model with a "maximally old" age of 2.6 Gyr and a moderate extinction $E(B-V) = 0.4$ provides the best fit to both galaxies, and we conclude that the red J_s-K_s colors of these objects are most likely the result of their evolved stellar populations. The SEDs of galaxies 1195 and 1458 are almost certainly affected by emission from their AGNs, which is difficult to model. When the continuum contributions of the AGNs are ignored, galaxy 1458 is best fitted by a constant star formation model with age 1.4 Gyr and $E(B-V) = 0.3$, and 1195 by a model with age 1.7 Gyr and $E(B-V) = 0.5$. The highest redshift galaxy in our sample, 1656, is not well fitted by simple models. Good fits are obtained for composite models of a young, dust-free component and a second young component that is heavily obscured, having $E(B-V) \sim 1.5$ (see Fig. 2).

For galaxy 1195, the contribution of Lyα emission to the B-band flux (30%–40%) had to be taken into account in the model fitting. On 2002 January 6, we obtained a 1200 s H-band spectrum with NIRSPEC on the Keck II telescope (inset in Fig. 2). The spectrum shows the redshifted lines [O III] λ4959, 5007; Hβ is undetected. The lines contribute 0.12 ± 0.04 mag to the H-band flux, consistent with the observed offset from the best-fitting model spectrum. Since 1195 is by far the strongest Lyα emitter in our sample, this result suggests that the contribution of line emission to the NIR fluxes is generally small for J_s-K_s selected galaxies.

We conclude that the red J_s-K_s colors are probably produced by evolved stellar populations and, in one case, a dusty young population. The median age of 1.7 Gyr is higher than the median age of $\sim 3 \times 10^8$ yr for LBGs, derived using the same models (Shapley et al. 2001; Papovich et al. 2001).

5. DISCUSSION

The spectroscopic redshifts demonstrate that $z \gtrsim 2$ galaxies can be selected efficiently by J_s-K_s colors alone. The criterion $J_s-K_s > 2.3$ is not extreme but selects galaxies whose rest-frame optical colors are similar to those of normal nearby galaxies: for $z = 2.7$, our J_s-K_s limit corresponds to $U-V \gtrsim 0.1$ in the rest frame, and a local sample thus selected would include almost all luminous galaxies (e.g., Jansen et al. 2000).

The surface density of $J_s-K_s > 2.3$ galaxies in the MS 1054−03 field is $1.09^{+0.20}_{-0.16}$ arcmin^{-2} to $K = 21$. If our small spectroscopic sample is representative of the general population, ∼20% are at low redshift, and the surface density of $z > 2$ optical-break galaxies is ≈0.9 arcmin^{-2} (ignoring the lensing effect of the foreground cluster). The Poissonian errors imply 65% confidence limits of 0.7–1.1. However, significant field-to-field variations exist: there are no $J-K > 2.3$ galaxies to $K = 21$ in the Hubble Deep Field–North (Fernández-Soto, Lanzetta, & Yahil 1999), whereas the surface density in the HDF-S is similar to that in the ∼5 times larger MS 1054−03 area. Additional errors due to galaxy correlations increase the upper limits but leave the lower limits relatively unchanged (see, e.g., Daddi et al. 2000). Based on the observed clustering of $J_s-K_s > 2.3$ galaxies in the HDF-S (Daddi et al. 2003), we find a 2 σ lower limit of ≈0.5 arcmin^{-2}.

The surface density can be compared with that of LBGs with $K_s \leq 21$, by integrating the K_s-band luminosity function determined for $z \approx 3$ LBGs by Shapley et al. (2001). We assume that the luminosity function does not evolve, and we use a template spectrum to calculate the dependence of M_K^* on redshift. Integrating over the redshift range 2.0–3.5 we find a surface density of ≈2.0 arcmin^{-2} to $K_s = 21$, twice the density of optical-break galaxies. This result is quite sensitive to the assumption that the redshift distribution of optical-break galaxies is a top hat with a lower bound of 2.0. Integrating over the redshift range 2.4–3.5 reduces the density to ≈0.9 arcmin^{-2}, and we conclude that the surface density of optical-break–selected galaxies is 0.5–1 times that of Lyman break–selected galaxies in the same redshift range. These numbers are broadly consistent with results obtained for fainter samples in the HDF-S (Franx et al. 2003).

Optical-break galaxies are underrepresented in samples selected by the Lyman break technique: only two out of 40 galaxies observed in J and K_s by Shapley et al. (2001) satisfy our selection criterion. Most optical-break galaxies in the MS 1054−03 field are too faint in the rest-frame UV to be selected as LBGs in ground-based surveys: ∼70% of galaxies with $K_s < 21$ have $R_{AB} > 25.5$. As shown in Franx et al. (2003), the overlap is even smaller for the fainter HDF-S sample. We note, however, that because of obvious selection effects, four of the five galaxies confirmed by optical spectroscopy are brighter than this limit and probably would be selected as LBGs if at the appropriate redshift.

The most straightforward (but not unique) interpretation of the newly identified population is that they are evolved descendants of galaxies that started forming stars at redshifts $z > 4$. As shown in Franx et al. (2003), their typical mass-to-light ratios are probably higher than those of galaxies selected by the Lyman break technique; hence, they may be the most massive galaxies yet identified at $z > 2$ and could be progenitors of early-type galaxies and bulges. Interestingly, the five confirmed $z > 2$ galaxies alone may already place limits on galaxy formation models. They constitute ≈1.5% of the $K_s < 20$ counts (e.g., Maihara et al. 2001; Labbé et al. 2003), whereas current semianalytical galaxy formation models have predicted that galaxies beyond $z \sim 2$ should essentially be absent in such bright samples (see Cimatti et al. 2002). The fraction is even higher (∼5%) when galaxies without spectroscopic redshift are included.

Surveys over larger areas will help us to establish the surface density with greater confidence. More spectroscopy is needed to determine the redshift distribution and AGN fraction better. Finally, NIR spectroscopy for more galaxies is needed to determine the contribution of emission lines to the broadband fluxes.

We thank Henk Hoekstra for computing the lens magnifications, Alice Shapley and Aaron Barth for useful discussions, and the referee, Pat McCarthy, for constructive comments that improved this Letter. P. G. v. D. acknowledges support from NASA through the *SIRTF* Fellowship program. The authors wish to extend special thanks to those of Hawaiian ancestry on whose sacred mountain we are privileged to be guests. Without their generous hospitality, many of the observations presented herein would not have been possible.

REFERENCES

Barger, A. J., Cowie, L. L., Mushotzky, R. F., & Richards, E. A. 2001, AJ, 121, 662
Baugh, C. M., Cole, S., Frenk, C. S., & Lacey, C. G. 1998, ApJ, 498, 504
Bolzonella, M., Miralles, J.-M., & Pelló, R. 2000, A&A, 363, 476
Calzetti, D., Armus, L., Bohlin, R. C., Kinney, A. L., Koornneef, J., & Storchi-Bergmann, T. 2000, ApJ, 533, 682
Cimatti, A., et al. 2002, A&A, 391, L1
Daddi, E., Cimatti, A., Pozzetti, L., Hoekstra, H., Röttgering, H. J. A., Renzini, A., Zamorani, G., & Mannucci, F. 2000, A&A, 361, 535
Daddi, E., et al. 2003, ApJ, in press (astro-ph/0303165)
Ferguson, H. C., Dickinson, M., & Papovich, C. 2002, ApJ, 569, L65
Fernández-Soto, A., Lanzetta, K. M., & Yahil, A. 1999, ApJ, 513, 34

Franx, M., et al. 2003, ApJ, 587, L79
Hoekstra, H., Franx, M., & Kuijken, K. 2000, ApJ, 532, 88
Hu, E. M., Cowie, L. L., & McMahon, R. G. 1998, ApJ, 502, L99
Jansen, R. A., Franx, M., Fabricant, D., & Caldwell, N. 2000, ApJS, 126, 271
Labbé, I., et al. 2003, AJ, 125, 1107
Madau, P., Ferguson, H. C., Dickinson, M. E., Giavalisco, M., Steidel, C. C., & Fruchter, A. 1996, MNRAS, 283, 1388
Magorrian, J., et al. 1998, AJ, 115, 2285
Maihara, T., et al. 2001, PASJ, 53, 25
McCarthy, P. J., et al. 2001, ApJ, 560, L131
Murray, N., Chiang, J., Grossman, S. A., & Voit, G. M. 1995, ApJ, 451, 498
Oke, J. B., et al. 1995, PASP, 107, 375
Papovich, C., Dickinson, M., & Ferguson, H. C. 2001, ApJ, 559, 620
Shapley, A. E., Steidel, C. C., Adelberger, K. L., Dickinson, M., Giavalisco, M., & Pettini, M. 2001, ApJ, 562, 95
Shapley, A. E., Steidel, C. C., Pettini, M., & Adelberger, K. L. 2003, ApJ, in press (astro-ph/0301230)
Smail, I., Ivison, R. J., Owen, F. N., Blain, A. W., & Kneib, J.-P. 2000, ApJ, 528, 612
Steidel, C. C., Adelberger, K. L., Giavalisco, M., Dickinson, M., & Pettini, M. 1999, ApJ, 519, 1
Steidel, C. C., Giavalisco, M., Pettini, M., Dickinson, M., & Adelberger, K. L. 1996, ApJ, 462, L17
Steidel, C. C., Hunt, M. P., Shapley, A. E., Adelberger, K. L., Pettini, M., Dickinson, M., & Giavalisco, M. 2002, ApJ, 576, 653
van Dokkum, P. G., Franx, M., Fabricant, D., Illingworth, G. D., & Kelson, D. D. 2000, ApJ, 541, 95