Can we relate the high-\( z \) galaxy results to what we have learned about galaxy formation from nearby galaxies?

\[ \frac{1}{(1+z)^4} \] surface brightness dimming means that highest surface brightness components (i.e. starbursts; hypernormal break galaxies) are easiest to detect.

- We see significant numbers of galaxies with 'old' stellar populations (~1 Gyr) at \( z = 2-3 \).
- Does this mean that ellipticals formed via monolithic collapse at high redshift, instead of via mergers, after all?

- No; galaxy SIZES at these high redshifts are much smaller (\( r_e < 1 \) kpc, of 5 kpc at \( z = 0 \)).
- These small galaxies may have formed in gas-rich mergers at very high redshift. 'Dry' (dissipationless) mergers may then increase size.
Spatial Density and Colors of Massive Galaxies at \( 2 < z < 3 \)

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The main result of our analysis is that massive galaxies at \( z \approx 2.5 \) 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 Lyman forest), we calculated synthetic colors in Steidel’s \( U_G R \) system. To qualify as an LBG, an object has to have \( R_{AB} < 25.5 \) and synthetic \( U_G R \) 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. Figure 2 illustrates the LBGs 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.

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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5. DISCUSSION

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An LBG in this definition is therefore an object that has \( R_{AB} < 25.5 \), \( 2 < z < 3 \), and is either a classical “U-dropout” or a BX/BM object.

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.
We present HST/NICMOS+ACS and Spitzer IRAC+MIPS observations of 41 galaxies at 2 < z < 3.5 in the FIRES MS 1054 field with red and blue rest-frame optical colors. About half of the galaxies are very compact (effective radii \( r_e < 1 \) kpc) at rest-frame optical wavelengths; the others are extended (1 kpc < \( r_e < 10 \) kpc). For reference, 1 kpc corresponds to 0.12" at \( z = 2.5 \) in the adopted cosmology. We separate actively star-forming galaxies from quiescent galaxies by modeling their rest-frame UV--NIR SEDs. The star-forming galaxies span the full range of sizes, while the quiescent galaxies all have \( r_e < 2 \) kpc. In the redshift range where MIPS 24 \( \mu \)m imaging is a sensitive probe of reradiated dust emission (\( z < 2.5 \)), the 24 \( \mu \)m fluxes confirm that the light of the small quiescent galaxies is dominated by old stars, rather than dust-enshrouded star formation or AGN activity. The inferred surface mass densities and velocity dispersions for the quiescent galaxies are very high compared to those in local galaxies. The galaxies follow a Kormendy relation (between surface brightness and size) with approximately the same slope as locally, but shifted to brighter surface brightnesses, consistent with a mean stellar formation redshift of \( z_f \sim 5 \). This paper demonstrates a direct relation between star formation activity and size at \( z \sim 2.5 \) and the existence of a significant population of massive, extremely dense, old stellar systems without readily identifiable counterparts in the local universe.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: fundamental parameters — galaxies: high-redshift — galaxies: structure — infrared: galaxies

1. INTRODUCTION

In the local universe, galaxy structure correlates with physical properties such as star formation rate (SFR) and history, mass, environment, gas and dust content, metallicity, etc. This is likely a consequence of the fact that star formation activity scales with environment and structure (bulge-to-disk ratio) scales with mass (Kauffmann et al. 2004). High-density environments are dominated by early-type galaxies, which are homogeneously old, red, quiescent, and with low dust contents, while lower density environments are dominated by late-type galaxies, which on average are bluer, less massive, and show a range of ages, dust contents, star formation histories, metallicities, etc. (e.g., Goto et al. 2004; Baldry et al. 2006). Observations suggest that these correlations exist out to at least \( z \sim 1.4 \), where clusters are still dominated by uniformly large, old, red early-type galaxies with little ongoing star formation and dust, although the fraction of blue late-type galaxies in clusters increases with redshift (e.g., Blakeslee et al. 2003; Toft et al. 2004; Bell et al. 2004; McIntosh et al. 2005; Lidman et al. 2004; Mullis et al. 2005; Cooper et al. 2007; Cassata et al. 2007). Understanding the epoch and nature of the onset of these relations is a key issue for understanding galaxy formation, and it is essential to push simultaneous studies of structure and star formation properties of galaxies to higher redshifts.

Until recently, most work on high-redshift galaxies was done using rest-frame UV-selected Lyman break galaxies (LBGs), which were thought to be representative of the high-redshift galaxy population. A Hubble Space Telescope (HST) study comparing the optical (rest-frame UV) WFPC2 and near-infrared (NIR; rest-frame optical) NICMOS structure of LBGs in the Hubble Deep Field–North (HDF-N) showed that these were similar (Dickinson 2000). This result discouraged further NICMOS observations of high-redshift galaxies in the following years, since NICMOS observations are much less efficient than optical WFPC2 and Advanced Camera for Surveys (ACS) observations. In a number of studies (Giavalisco et al. 1996; Lowenthal et al. 1997; Dickinson 2000; Ferguson et al. 2004; Bouwens et al. 2004) it was assumed that rest-frame UV structural properties (such as Hubble type and size) were representative of the rest-frame optical structural properties (which trace the bulk of the stellar mass distribution and are related to the dynamical state of the galaxies). The similarity of the rest-frame optical and UV structural properties of high-redshift galaxies in the HDF-N was later confirmed in a more detailed
mass-normalized comparison further supports the similarity of the size distributions. The K-S test yields a 50% chance that the mass-normalized $r_e$ values were drawn from the same parent distribution. Furthermore, it can be seen that the sizes of the galaxies in the sample are on average smaller by a factor of about 3 than late-type galaxies of similar mass in the local universe (see § 8.1 for more details). Here and in the following section we normalize all sizes using the local mass-size relation of late-type galaxies in SDSS (Shen et al. 2003) as the vast majority of the galaxies in the sample are best fitted by exponential disk surface brightness profiles. Alternatively, we could have normalized the sizes of galaxies with de Vaucouleurs-like surface brightness profiles, by the local relation for early-type galaxies; however, as the local early- and late-type relations are very similar in the mass range of the “de Vaucouleurs” law galaxies in the sample (see Fig. 10 below), it would not significantly change the normalized sizes.

While the sizes of the galaxies do not seem to depend on their $J-K$ color, there is a strong correlation with star formation activity. In Figure 8 we compare the size distribution of star-forming and quiescent galaxies. There is a clear trend that quiescent galaxies are smaller than star-forming galaxies. Four of the quiescent DRGs (57%) are unresolved in the NICMOS images, while none of the star-forming DRGs are unresolved. As shown in Figure 8 (right panel) the size difference is even more pronounced when normalized by the local mass-size relation.

From this figure it can be seen that the quiescent galaxies are on average smaller by a factor of about 5 than late-type galaxies in the local universe, while star-forming galaxies on average are smaller by a factor of about 2. The mass distribution of the star-forming and quiescent DRGs is similar (the K-S test yields an 80% chance of them being drawn from the same parent mass distribution). It will be interesting to determine whether star-forming galaxies have lower mass densities or are dense systems with widely distributed star formation. In Figure 6 we compare the $n$-distributions of the resolved star-forming and quiescent galaxies. All of the resolved quiescent galaxies and 83% of the resolved star-forming galaxies are better fitted by exponential disk-like than de Vaucouleurs-like surface brightness profiles. This confirms the finding of Stockton et al. (2004) that galaxies with purely old stellar populations at $z \sim 2.5$ can have exponential surface brightness profiles. The K-S test yields a 54% chance of the $n$-values of quiescent and star-forming galaxies being drawn from the same parent distribution.

6. CORRELATIONS BETWEEN SIZE AND MIPS 24 $\mu$m EMISSION

At $1.5 < z < 2.5$ the 24 $\mu$m MIPS filter samples rest-frame $\sim$6–10 $\mu$m, and the 24 $\mu$m flux offers a powerful method for differentiating between galaxies with SEDs dominated by dusty star formation and/or AGNs, both of which produce substantial MIR emission, and quiescent galaxies whose stellar flux continues to drop longward of $\sim$2 $\mu$m (e.g., Webb et al. 2006). In pure starburst galaxies the MIR emission is dominated by polycyclic aromatic hydrocarbon (PAH) features, which are strong relative to the underlying dust continuum (e.g., Smith et al. 2007). The hard radiation field of an AGN destroys PAH carriers, and the continuum emission from hot small dust grains is strong throughout the MIR (Genzel & Cesarsky 2000; Laurent et al. 2000). At $z > 2.5$ the sensitivity to star formation is reduced drastically as the PAH features are redshifted out of the 24 $\mu$m band, so in the following we concentrate on the galaxies in our sample with $z < 2.5$, which leaves 19 DRGs and four DBGs. Assuming that the 24 $\mu$m flux is dominated by star formation, the PAH and MIR emission can be used to estimate the current SFR of the galaxies (Wu et al. 2005). Using an Arp 220 SED template, we extrapolated from 24 $\mu$m/(1 + $z$) flux to rest-frame 6.75 $\mu$m flux. We then estimated the total (8–1000 $\mu$m) infrared luminosity $L_{IR}$ through the observed 6.75 $\mu$m–$F_{VIR}$ relation calibrated locally with the Infra­red Space Observatory (Elbaz et al. 2002), which shows a factor of 2 scatter. This value can then be converted into an SFR using the $L_{IR}$–SFR relationship of Bell (2003) with an expected scatter of at least a factor of 2. Additional systematic uncertainties are introduced in the first step extrapolation. Adopting an M82-like template instead of the Arp 220 template leads to a factor of 2 lower SFR (Webb et al. 2006), while adopting the model templates of Dale & Helou (2002) can result in factors of 2–6 lower SFRs (Papovich et al. 2007). Uncertainties in the photometric redshifts translate into a factor of 2.5 uncertainty in the derived SFR (Papovich et al. 2006). Added in quadrature the expected uncertainties in 24 $\mu$m–SFR conversion amount to about a factor of $\approx$7.
Fig. 2.—Relations between size and (total) stellar mass (left panel) and between the average stellar density inside the effective radius and stellar mass (right panel). Large symbols with error bars are the quiescent $z \sim 2.3$ galaxies. Small symbols are SDSS galaxies, with galaxies that are not on the red sequence in light gray. The dotted lines indicate the expected location of galaxies with stellar velocity dispersions of 200, 300, and 500 km s$^{-1}$. The high-redshift galaxies are much smaller and denser than SDSS galaxies of the same stellar mass.

Uncertainties in the structural parameters of faint galaxies are difficult to estimate, as they are usually dominated by systematic effects. For each galaxy, we added the residual image of each of the other galaxies (excluding 1256-1967) in turn, repeated the fit, and determined the rms of the seven values obtained from these fits. The uncertainties listed in Table 1 are $2 \times$ these rms values, to account for additional systematic uncertainties. These were assessed by changing the size of the fitting region, scrambling the subpixel positions of the galaxies, and changing the drizzle grid.

The Keck images offer an independent test of the reliability of the fit parameters. Fitting the Keck images with a range of stellar PSFs (including stars in the field of view) gives results that are consistent with the NIC2 fits within the listed uncertainties. As an example, for 1030-1813, we find $r_{\text{e}} = 0.73$ kpc, $n = 1.6$, and $b/a = 0.32$ from the Keck image. If we used the Keck data, we will use the values derived from the higher signal-to-noise ratio (S/N) NIC2 images; our conclusions would not change if we were to use the Keck results for 1030-1813, 1256-0, and 1256-1967.

4. SIZES AND DENSITIES

The most remarkable aspect of the $z \sim 2.3$ galaxies is their compactness. The circularized effective radii range from 0.5 to 2.4 kpc, and the median is 0.9 kpc. To put this in context, this is smaller than many bulges of spiral galaxies (including the bulges of the Milky Way and M31, which have $r_{\text{e}} \approx 2.5$ kpc; van den Bergh 1999). In the left panel of Figure 2, the sizes are compared to those of SDSS galaxies. The SDSS data were taken from the New York University Value-Added Galaxy Catalog (Blanton et al. 2005) in a narrow redshift range, with various small corrections (M. Franx et al., in preparation). Dark gray points are galaxies on the red sequence, here defined as $u-g = 0.1 \log M + (0.6 \pm 0.2$). Stellar masses for the $z \sim 2.3$ galaxies were taken from Kriek et al. (2008a) and corrected to a Kroupa (2001) initial mass function (IMF). The median mass of the $z \sim 2.3$ galaxies is $1.7 \times 10^{11} M_\odot$. The median $r_{\text{e}}$ of SDSS red sequence galaxies with masses $(1.5-1.9) \times 10^{11} M_\odot$ is 5.0 kpc, a factor of $\sim 6$ larger than the median size of the $z \sim 2.3$ galaxies.

The combination of small sizes and high masses implies very high densities. The right panel of Figure 2 shows the relation between stellar density and stellar mass, with density defined as $\rho = 0.5M(H(4/3)_{\text{r}})$ (i.e., the mean stellar density within the effective radius, assuming a constant stellar mass-to-light [M/L] ratio with radius). The median density of the $z \sim 2.3$ galaxies is $3 \times 10^{10} M_\odot$ kpc$^{-3}$ (with a considerable rms scatter of 0.7 dex), a factor of $\sim 180$ higher than the densities of local red sequence galaxies of the same mass.

We note that it is difficult to determine the morphologies of the galaxies, as they are so small. Nevertheless, it is striking that several galaxies are quite elongated (see Fig. 1). The most elongated galaxies are also the ones with the lowest $n$-values (the correlation between $n$ and $b/a$ is formally significant at the $>99\%$ level), and a possible interpretation is that the light of a subset of the galaxies is dominated by very compact, massive disks (see § 5).

5. DISCUSSION

We find that all ($100\%,\%$) of the quiescent, massive galaxies at $z = 2.3$ spectroscopically identified by Kriek et al. (2006) are extremely compact, having a median effective radius of only 0.9 kpc. This result extends previous work at $z \sim 1.5$ (Trujillo et al. 2007; Longhetti et al. 2007; Cimatti et al. 2008) and confirms other studies at similar redshifts that were based on photometric redshifts and images of poorer quality (Zirm et al. 2007; Toft et al. 2007). Our study, together with the spectroscopy in Kriek et al. (2006) demonstrating that the $H$-band light comes from evolved stars, shows that the small measured sizes of evolved high-redshift galaxies are not caused by photometric redshift errors, active galactic nuclei, dusty starbursts, or measurement errors.

It is remarkable that all nine galaxies are so compact; even the largest galaxy in the sample (HDFS1-1849) is significantly offset from the relations of red galaxies in the nearby universe (see Fig. 2). We do not find any galaxy resembling a fully assembled elliptical or S0 galaxy, which means that such objects make up less than $\sim 10\%$ of the population of quiescent galaxies at $z \sim 2.3$. This result effectively rules out simple...
IR & sub-mm searches for high-z galaxies

Locally, starburst galaxies can be identified via emission from the cold dust they contain, in the far IR.

(eg M82, 'ULIRGs')

Ultra-luminous Infrared Galaxies $z \approx 0$:

Some of the most luminous objects $z \approx 0$

Most of light comes out in far-IR

Bolometric luminosities $> 10^{12} L_\odot$

These galaxies are mergers of gas-rich galaxies

Have large amounts of molecular gas in inner kpc;

(\underline{density} of molecular gas comparable to stellar density in giant ellipticals)

Dasyra et al 2006

Early IR spectra suggest that these are equal-mass or few-to-1 mass ratio mergers

Theoretical dynamical models associate these mergers with elliptical galaxy formation
High-$z$ equivalents of ULIRGs

cold dust emits $\lambda \sim 100 \mu m$ (far IR)

$z = 2-3 \Rightarrow$ peak shifts to $\sim 3-400 \mu m$
(sub-mm)

Detector technology changes .... now need to use a bolometer

eg SCUBA : Submm Common User Bolometer Array
or 15m JCMT. Cooled to 0.1K (eek!)

Observations (Smail et al 2002) at 450 & 850$\mu m$

What is the major problem with imaging
for single-dish telescopes at these long wavelengths?

$\rightarrow$ Resolution $\sim \frac{\lambda}{D}$ : 7.5 and 15 arcsec FWHM

So finding optical counterparts is doubly difficult:
paint, and a big area to search in.
Bolometer

From Wikipedia, the free encyclopedia

A bolometer is a device for measuring incident electromagnetic radiation. It was invented in 1878 by the American astronomer Samuel Pierpont Langley.

It consists of an "absorber", which is connected to a heat sink (area of constant temperature) through an insulating link. The result is that any radiation absorbed by the absorber raises its temperature above that of the heat sink—the higher the power absorbed, the higher the temperature will be.

A thermometer of some kind, attached to the absorber, is used to measure the temperature, from which the absorbed power can be calculated. In some designs the thermometer is also the absorber; in others the absorber and thermometer are separate; this is known as "composite design".

While bolometers can be used to measure radiation of any frequency, for most wavelength ranges there are other methods of detection that are more sensitive. However, for sub-millimetre wavelengths (from around 200 μm to 1 mm wavelength), the bolometer is the most sensitive type of detector for any measurement over more than a very narrow wavelength range.

Bolometers are therefore used for astronomy at these wavelengths. However, to achieve the best sensitivity, they must be cooled down to a fraction of a degree above absolute zero (typically from 50 millikelvins to 300 mK); this makes their operation technically somewhat challenging.

The term bolometer is also used in high-energy physics (particle physics) to designate an unconventional particle detector. They use the same principle described above. The bolometers are sensitive not only to light but to every form of energy.

More conventional particle detectors are often sensitive to ionization effect of ionizing particles. Bolometer are almost directly sensitive to the energy left inside the absorber. For this reason they can be used not only for ionizing particle and photons, but also for non-ionization particle, for any sort of radiation and even to search for unknown forms of mass or energy (like dark matter). They are very slow and they have a high dead time. They lack completely of any sort of discrimination. On the other hand, compared to more conventional particle detectors, they are extremely efficient in energy resolution and in sensitivity. They can be used to test very high radio-purity. They are also known as thermal detectors.

In principle the way of operation is similar to that of a calorimeter in thermodynamics. However the non-standing of many approximation usually taken while dealing with thermodynamic, the need of working at ultra low temperature, and the different aim of the device make the operational use rather different. In the jargon of the high energy physics, these devices are not called calorimeters since this term is already used for a different type of detector (see Calorimeter (particle physics)).

Their use as particle detectors is still at the developmental stage. Their usage as particle detectors was advice from the beginning of 20th century but the first regular use, even if in a pioneering way, was only in the 1980s because of the difficulty associated with having a system at cryogenic temperature.

Langley’s bolometer

The first bolometer used for infrared observatons by Langley had a very basic design: It consisted of two platinum strips, covered with lampblack, one strip was shielded from the radiation and one exposed to it. The strips formed two branches of a wheatstone bridge which was fitted with a sensitive galvanometer and connected to a battery.
Smail et al. used gravitational lenses to (a) magnify & (b) amplify the sub-mm sources by 2-3.

It is hard to identify optical counterparts, use $K$-band imaging and deep radio maps.

Q How might you estimate redshifts for these galaxies?

→ with great difficulty.

But they are plausibly $z > 3.2$.

Could be progenitors of today's ellipticals.

Q Why?
Figure 6. \(I\) - and \(K\)-band frames of the fields of the submm sources in our sample (excluding the two central cluster galaxies), ordered in terms of their apparent 850-\(\mu\)m fluxes. The 850-\(\mu\)m map of each source is overlayed as a contour plot on the \(I\)-band frame, after convolution with an 8-arcsec FWHM Gaussian for display purposes. Note that the \(I\)- and \(K\)-band frames represent a range in depth and resolution, but they have all been smoothed (with a 0.5-arcsec FWHM Gaussian) to enhance the visibility of faint features. We identify the various confirmed or candidate counterparts and other galaxies discussed in the text on the individual panels. Each panel is 25-arcsec square and has north to the top and east to the left.

We show in Fig. 6 the submm maps of each of the 15 cluster background sources overlayed on the deep \(I\)-band exposures of these frames. For the sources in A2390, CI 2244−02 and most of those in CI 0024+16, we use \(HST\) F814W \((I)\) images degraded to the same seeing and pixel scale as ground-based near-IR images (see Section 4.2). For the remaining fields we have used deep, ground-based \(I\)-band frames: for CI 0939+47 and MS 0440+02 we use the Keck \(I\)-band imaging from Smail et al. (1999a) and for A1835 and A370 the Hale 5-m and CFHT imaging discussed in Smail et al. (1998).

However, in the course of this analysis it has become clear that identifying submm counterparts using optical data alone is a problematic process (Smail et al. 1998; Lilly et al. 1999). With the exception of a handful of three unusual and optically bright counterparts: SMM J02399−0136 (Ivison et al. 1998); SMM J02399−0134 (Soucail et al. 1999) and SMM J14011+0252 (Ivison et al. 2000a), the majority of the submm sources cannot be reliably identified on the basis of just optical imaging, irrespective of its depth (Section 4.6; Smail et al. 1998).

4.2 Near-infrared counterparts

To more reliably identify counterparts to the 15 submm sources we next obtained near-IR imaging of our fields. The goal is to combine this with the deep optical data, to attempt to locate any counterparts within the submm error box on the basis of their unusual optical–near-IR colours, e.g. \((I - K) \gtrsim 5\). For this purpose the depth required in the \(K\)-band was set by the depth of the available \(I\)-band images, \(I \sim 25-26\), with the deepest being the multi-orbit \(HST\) exposures, leading to a limit of \(K \sim 20-21\) for our observations. In most cases, integrating fainter in \(K\) might produce additional candidate counterparts but we would be unable to identify these as unusual on the basis of their very red colours from our existing optical images. In the few cases where more accurate positional information about a probable submm source is available, from either millimetre-wave continuum or radio interferometry maps, deeper \(K\)-band observations have been obtained (e.g. Ivison et al. 2000a; Frayer et al. 2000).

The near-IR observations of our fields were undertaken in typically good conditions during several observing runs in late 1998 and early 1999 using the IRCAM3 and UFTI cameras on the 3.8-m UKIRT.\(^3\) Observations consist of deep \(K\)-band exposures (with \(J\)- or \(H\)-band observations of the brighter sources detected in \(K\)).

Data were obtained with IRCAM3 on the nights of 1998 July 11−16 and 18, September 10 and 19, October 9 and 1999 February

\(^3\)UKIRT is operated by the Joint Astronomy Centre on behalf of the Particle Physics and Astronomy Research Council of the United Kingdom.

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