IRAC MID-INFRARED IMAGING OF THE HUBBLE DEEP FIELD SOUTH: STAR FORMATION HISTORIES AND STELLAR MASSES OF RED GALAXIES AT Z > 2

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ABSTRACT

We present deep 3.6−8 μm imaging of the Hubble Deep Field South with IRAC on the Spitzer Space Telescope. We study Distant Red Galaxies (DRGs) at z > 2 selected by J−Ks > 2.3 and compare them to a sample of Lyman Break Galaxies (LBGs) at z = 2−3. The observed UV-to-8 μm spectral energy distributions are fit with stellar population models to constrain star formation histories and derive stellar masses. We find that 70% of the DRGs are best described by dust-reddened star forming models and 30% are well fit with old and “dead” models. Using only the I−Ks and Ks−4.5 μm colors we can effectively separate the two groups. The dead systems are among the most massive at z > 2.5 (mean stellar mass < M* > = 0.8 × 10^{11} M_☉) and likely formed most of their stellar mass at z > 5. To a limit of 0.5 × 10^{11} M_☉ their number density is ~10× lower than that of local early-type galaxies. Furthermore, we use the IRAC photometry to derive rest-frame near-infrared J, H, and K fluxes. The DRGs and LBGs together show a large variation (a factor of 6) in the rest-frame K-band mass-to-light ratios (M/L_K), implying that even a Spitzer 8 μm–selected sample would be very different from a mass-selected sample. The average M/L_K of the DRGs is about three times higher than that of the LBGs, and DRGs dominate the high-mass end. The M/L_K ratios and ages of the two samples appear to correlate with derived stellar mass, with the most massive galaxies being the oldest and having the highest mass-to-light ratios, similar as found in the low-redshift universe.

Subject headings: galaxies: evolution — galaxies: high redshift — infrared: galaxies

1. INTRODUCTION

Galaxies at z > 2 exhibit very diverse properties: they range from the blue Lyman Break Galaxies (LBGs) which are bright in the rest-frame ultraviolet (Steidel et al. 1996a,b) to the Distant Red Galaxies (DRGs) which are generally faint in the rest-frame UV and have fairly red rest-frame optical colors. The DRGs are selected in the observers’ near-infrared (NIR) by the simple criterion J−Ks > 2.3 (Franx et al. 2003, van Dokkum et al. 2003). The variety in the galaxy population at z > 2 is comparable to that seen in the local universe, where colors range from very blue for young starbursting galaxies to very red for old elliptical galaxies. An urgent question is what causes the red colors of DRGs at z > 2. Are they “old and dead”, or are they actively star forming and more dusty than U-dropout galaxies?

First analyses of the optical-to-NIR Spectral Energy Distributions (SEDs) and spectra have suggested that both effects play a role: they have higher ages, contain more dust, and have higher mass-to-light (M/L) ratios in the rest-frame optical than LBGs (Franx et al. 2003, van Dokkum et al. 2004, Forster Schreiber et al. 2004; F04). Furthermore, many have high star formation rates > 100 M_☉ yr^{-1} (van Dokkum et al. 2004, F04). Unfortunately, the number of DRGs with rest-frame optical spectroscopy is very small. Inferences inevitably depend on SED fitting, which has large uncertainties (see e.g., Papovich, Dickinson, & Ferguson 2001). The SED constraints on the stellar and dust content are expected to improve significantly by extending the photometry to the rest-frame near-infrared.

Here we present the first results on rest-frame NIR photometry of DRGs and LBGs in the Hubble Deep Field South (HDFS) as observed with the Infrared Array Camera (IRAC; Fazio et al. 2004) on the Spitzer Space Telescope. Where necessary, we assume an Ω_M = 0.3, Ω_Λ = 0.7, cosmology with H_0 = 70 km s^{-1} Mpc^{-1}, and a Salpeter Initial Mass Function (IMF) between 0.1 and 100 M_☉. Magnitudes are expressed in the AB photometric system unless explicitly stated otherwise.

2. THE OBSERVATIONS, PHOTOMETRY, AND SAMPLE SELECTION

We have observed the 5 arcmin² HDFS/WFPC2 field with the IRAC camera integrating 1 hour each in the mid-infrared (MIR) 3.6, 4.5, 5.8, and 8 μm—bands. The observations, data reduction, and photometry will be described by Labbé et al. (in preparation). Briefly, we reduced and calibrated the data using standard procedures (e.g., Barmby et al. 2003). The limiting depths at 3.6, 4.5, 5.8, and 8 μm are 25.0, 24.6, 22.6, and 22.5 mag, respectively (5σ, 3″ diameter aperture). We PSF-matched the IRAC images and a very deep Ks—image (Labbé et al. 2003) to the 8 μm—band. Nearby sources were fitted and subtracted to avoid confusion (see Labbé et al. 2004). We measured fluxes in 4″ diameter apertures. The Ks−IRAC colors were then combined with the HDFS-catalog
of Labbé et al. (2003) resulting in 11-band photometry from 0.3 to 8 \mu m. In addition to the photometric errors, we add in quadrature an error of 10% to reflect absolute calibration uncertainties of IRAC.

We selected DRGs in the field of the HDFS using the criteria of Franx et al. (2003) yielding 14 galaxies with photometric redshifts (Rudnick et al. 2003) in the range 1.9 < z < 3.8. One blended source was excluded. In addition, we selected isolated LBGs in the same field to the same \( K_s \)-band limit and in the same redshift range, using the \( U \)-dropout criteria of Madau et al. (1996) on the WFPC2 imaging (Casertano et al. 2000). The two samples are complementary, with only 1 source in common. For both samples, the mean redshift is \( z = 2.6 \) with a standard deviation of 0.5\textsuperscript{11}.

3. RED GALAXIES AT Z > 2: OLD OR DUSTY OR BOTH?

In Fig. 1 we analyze the \( I - K_s \) versus \( K_s - 4.5 \mu m \) color-color diagram of two samples of \( z > 2 \) galaxies. Distant Red Galaxies (DRGs; filled circles and stars), occupy a different color region than \( z \sim 2.5 \) Lyman Break Galaxies (LBGs; diamonds). DRGs that are best described by an old single-age burst model (SSP; stars) have colors distinct from those better described by constant star-forming models (CSF) and dust, indicating that IRAC fluxes may help in separating these populations. The curves show the color-evolution tracks of Bruzual & Charlot (2003) models at a fixed \( z = 2.6 \): a SSP model with ages ranging from 0.3 to 3 Gyr (dashed line) and two CSF models with ages ranging from 0.1 to 3 Gyr, and reddenings of \( A_V = 0.6 \) and \( A_V = 2.0 \) respectively (solid lines). The vector indicates a reddening of \( A_V = 1 \) mag for a Calzetti et al. (2000) law.

3.1. Dead galaxies at \( z = 2-3 \)

Three of 13 DRGs (indicated by star symbols in Fig. 1) lie well outside the area of constant star-forming models. Their \( I - K_s \) colors are too red for their \( K_s - 4.5 \mu m \) color and they lie close to the line of an old single-age burst model with ages of 2–3 Gyr. The candidate old, passive galaxies are shown in Fig. 2. Their SEDs are very well fit by an old single burst population. The gray model curves are predictions based on fits to the exceptionally deep optical/NIR data only, demonstrating that the Spitzer fluxes lie very close to the expected values. Dead galaxies have blue \( K_s - 4.5 \mu m \) colors and with Spitzer we can now effectively separate them from dusty star-forming DRGs, which are red in \( K_s - 4.5 \mu m \).

Models with ongoing star-formation and dust-reddening fit the SEDs badly. Star-formation histories (SFHs) with exponentially declining star-formation rates (SFRs) and timescales > 300 Myr can be ruled out at the 99.9% confidence level. For the marginally acceptable models, the ratio of on-going to past-average SFR is \( SFR(t)/<SFR> = 0.001 \) indicating that these 3 galaxies are truly “red and dead”. The best-fit ages and implied formation redshifts depend on the assumed metallicity \( Z \), as expected. Super-Solar \( Z = 0.05 \) models give a mean age of \( < t > = 1.4 \) Gyr and mean formation redshift \( < z_f > = 5 \), solar \( Z = 0.02 \) models yield \( < t > = 2.9 \) Gyr and \( < z_f > = 5 \), while sub-solar metallicity models fail to provide good fits to the IRAC fluxes as they are too blue. Hence we infer from the models that the “dead” galaxies had formed most of their stellar mass by \( z \sim 5 \) (\( Z = 0.05 \)) or much earlier \( z \gg 5 \) (\( Z = 0.02 \)).

The number density of “dead” galaxies is 1.9 \( \times 10^{-4}h_7^2 \) Mpc\(^{-3} \), assuming a top hat redshift distribution between \( z = 2 \) and 3. For stellar masses > 0.5 \( \times 10^{11}M_\odot \) and the same IMF, that number density is 10\( \times \) lower than that of early-type galaxies in the nearby universe (Bell et al. 2003). Obviously, the sampled volume is too small to allow firm conclusions, but the result is indicative of strong evolution of passive galaxies from \( z = 2.5 \) to \( z = 0 \).

3.2. Dusty star forming galaxies

In Fig. 2 we show the SEDs for 3 of the 8 DRGs whose optical/NIR fluxes were better fit with CSF models and reddening by a Calzetti et al. (2000) dust law. The observed MIR flux points are often different from predictions based on shorter wavelengths, especially where the flux density \( F_\nu \) was still rising at the observed \( K_s \)-band. Hence, for the very dusty DRGs (\( A_V > 1.5 \)) the MIR fluxes help to better constrain the age and dust in the models. The average ages and extinction of the fits changed mildly after inclusion of the IRAC data: from \( < t > = 1.1 \) to 1.3 Gyr, and \( < A_V > = 1.9 \) to 1.5 mag, respectively.

Finally, two remaining galaxies could not be fit well by any model, most likely due to emission line contamination. One of them is spectrscopically confirmed as a very strong Lyman-\( \alpha \) emitter (Wuyts et al. in preparation). However, the generally good fits to the UV-to-8\mu m SEDs of the DRGs indicate that the red \( J_b - K_b \) colors were caused by old age and

\textsuperscript{11} The photometric redshift accuracy of DRGs from other studies is \( |z_{\text{spec}} - z_{\text{phot}}|/(1 + z_{\text{phot}}) \approx 0.1 \) (F04, Wuyts et al. in preparation). The estimate is based on direct comparison of 16 galaxies with both photometric and spectroscopic redshifts. Uncertainties in rest-frame magnitudes and model parameters are based on Monte Carlo simulations that take into account uncertainties in the observed fluxes and redshift estimates.
dust-reddened star light, and not other anomalies. We note that one of the dead galaxies (see Fig. 1) has an apparent flux excess at 8µm, suggesting the presence of an obscured AGN which starts to dominate the flux in the rest-frame K-band (see e.g., Stern et al. 2005).

4. MASS-TO-LIGHT RATIO VARIATIONS AT Z = 2–3

We next study the M/L ratios inferred from the SED fits described above, adopting the best fitting SFH (SSP or CSF). Figure 3a shows the modeled M/L\_K (rest-frame K) versus rest-frame U–V. The curves show the dust-free BC03 model M/L\_K ratios. Galaxies generally lie to the red of the model curves as a result of dust attenuation. The fits imply a large range in M/L\_K for DRGs and LBGs together (a factor of 6). Furthermore, the M/L\_K ratio correlates with rest-frame U–V color, where galaxies red in the rest-frame optical have higher M/L\_K ratios than blue galaxies. The average M/L\_K of the DRGs is 0.33 ± 0.04, about three times higher than that of the LBGs. Figure 3b shows the derived M/L\_K against the derived age. The M/L\_K correlates well with the age, as expected from the models. The role of extinction is greatly reduced in the rest-frame K-band, implying that the differences in the M/L\_K ratios for DRGs and LBGs are driven by age differences.

Figure 3c shows the M/L\_K ratio against stellar mass M\_\ast. DRGs dominate the high-mass end. The highest-mass galaxies (> 0.5 \times 10^{11} M_\odot) in this sample all have high M/L\_K ratios, and here the M/L\_K ratio does not depend strongly on M\_\ast. At lower masses galaxies have much lower M/L\_K ratios. This may be a selection effect caused by our magnitude cut-off, as we would miss low-mass galaxies with high M/L\_K. However, high-mass galaxies with low M/L\_K would be detected if they existed, hence the lower envelope of the M/L\_K versus M\_\ast distribution is real. Two intriguing possibilities are that the mean M/L\_K decreases towards lower stellar mass, or that the intrinsic scatter in M/L\_K increases.

Our DRGs and LBGs were selected in the observed K\_s-band (rest-frame V-band). We find a large variation in M/L\_V (a factor of 25), hence selection effects play a major role in NIR studies at high redshift. Selection using MIR observations with Spitzer would improve the situation, but the wide range in M/L\_K ratios and ages found here indicates that even a IRAC 8µm—selected sample would still be very different from a mass-selected sample.

5. DISCUSSION AND CONCLUSIONS

We have presented rest-frame UV-to-NIR photometry of a sample of DRGs and LBGs at z = 2–3 in the HDFS. These galaxies span a wide range in properties, similar to low-redshift galaxies. The rest-frame NIR photometry from IRAC helps significantly: first, by allowing us to separate “old and dead” from dust star forming DRGs using only the observed I, K\_s, and 4.5µm-band, and second, by improving model constraints on the heavily obscured DRGs.

The wide range in galaxy properties at z = 2.5 raises several important issues. First, it demonstrates it is impossible to obtain mass-selected samples photometrically. Even in the rest-frame K-band, the M/L ratio varies by a factor of 6 for the DRGs and LBGs in the HDFS. Second, we need to understand what produces these variations. If a relation between total stellar mass and M/L\_K exists (see Fig. 3c) then stellar mass might be driving the variations. Deeper IRAC data is needed to establish this well, as incompleteness effects may play a role. It is tantalizing that Kauffmann et al. (2003) find a similar correlation at z = 0.1, with the most massive galaxies being the oldest and having the highest M/L ratios. The authors also found that above a stellar mass M\_\ast = 6 \times 10^{10} M_\odot galaxy properties correlate only weakly with M\_\ast, similar to what we find at z = 2–3. The simplest explanation is that we observe the same galaxies at z = 0.1 and z = 2.5, although we note that hierarchical formation scenarios predict significant merging for galaxies at z > 2. Alternatively, we observe merging processes occurring at a critical mass of about 6 \times 10^{10} M_\odot. A partial explanation may be a simple relation between mass and metallicity: higher mass galaxies might have higher metallicity, and
Fig. 3.— The mass-to-light ratios in the rest-frame $K$-band ($M/L_K$) of distant red galaxies (DRGs) and $z = 2–3$ Lyman break galaxies (LBGs). Symbols are as in Fig. 1. (a) $M/L_K$ versus rest-frame $U-V$ color, showing a clear correlation. On top we indicate the corresponding observed $J_K$ color and the $J_K - K > 2.3$ limit (upward arrow). Color tracks of an SSP (dotted line) and CSF model (dashed line) are shown. (b) The relation between $M/L_K$ and best-fit age. The $M/L_K$ is more sensitive to the age of the stellar population than to dust extinction, hence the DRGs are on average older, not just more dusty versions of LBGs. (c) $M/L_K$ versus stellar mass. The highest-mass galaxies all have high $M/L_K$ ratios. The mass completeness limit (downward arrow) corresponds to our observed $K_s, \text{tot} = 22.5$ magnitude cut-off and a maximal $M/L_K$. A selection by rest-frame $K$-light corresponds to taking everything to the right of the constant $L_K$ line (dashed line). Obviously this is still far from a vertical cut-off which would represent a selection by stellar mass.

Thus be redder.

It is very noteworthy that there are “red and dead” galaxies at $z = 2–3$. Previous authors found such galaxies at $z = 1–2$ (e.g., Cimatti et al. 2004; McCarthy et al. 2004). Whereas the number density of “dead” galaxies at $z = 2.5$ is probably much lower than at $z = 0$, the mere existence of these systems at such high redshift raises the question what caused such a rapid and early decline in star formation. Our model fits imply that their star formation stopped by $z = 5$ or higher, close to or during the epoch of reionization. Possibly a strong feedback mechanism caused this, such as an AGN or galactic-scale outflow. We note that these galaxies are among the most massive galaxies at $z = 2.5$, and hence were probably at the extreme tail of the mass function at $z = 5$.

Obviously, many questions remain unanswered by this study. Only a very small field has been studied, and similar studies on wider fields are necessary. Finally, the $M/L$ ratios derived here remain model dependent and vary with the assumed SFH, metallicity, and IMF (e.g., Bell et al. 2003). Direct mass determinations are presently very challenging, but are becoming more important to understand the $z = 2–3$ galaxy population.

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REFERENCES

Barmby, P., et al. 2004, ApJS, 154, 97
Bell, E. F., et al. 2003, ApJS, 149, 289
Bruzual, G. & Charlot, S. 2003, MNRAS, 344, 1000 (BC03)
Casertano, S. et al. AJ, 120, pp. 2747–2824, 2000
Calzetti, D., et al. 2000, ApJ, 533, 682
Cimatti, A., et al. 2004, Nature, 430, 184
Fazio, G. G., et al. 2004, ApJS, 154, 10
Franx, M. et al. 2003, ApJ, 587, L79
Förster Schreiber, N. M., et al. 2004, ApJ, 616, 40 (F04)
Kauffmann, G., et al. 2003, MNRAS, 341, 54
Labbé, I., et al. 2003, AJ, 125, 1107
Labbé, I., 2004, Doctoral Thesis, Leiden University

Madau, P., et al. 1996, MNRAS, 283, 1388
McCarthy, P. J., et al. 2004, ApJ, 614, L9
Papovich, C., Dickinson, M., & Ferguson, H. C. 2001, ApJ, 559, 620
Rudnick, G., et al. 2003, ApJ, 599, 847
Steidel, C. C., et al. 1996, AJ, 112, 352
Steidel, C. C., et al. 1996b, ApJ, 462, L17
Stern, D., et al. 2005, ApJ, submitted (astro-ph/0410523)
van Dokkum, P. G. et al. 2003, ApJ, 587, L35
van Dokkum, P. G., et al. 2004, ApJ, 611, 703
Yan, H., et al. 2004, ApJ, 616, 63