NEAR-INFRARED BRIGHT GALAXIES AT $z \approx 2$. ENTERING THE SPHEROID FORMATION EPOCH?1

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ABSTRACT

Spectroscopic redshifts have been measured for nine $K$-band luminous galaxies at $1.7 < z < 2.3$, selected with $K_s < 20$ in the K20 survey region of the Great Observatories Origins Deep Survey (GOODS) area. Star formation rates (SFRs) of $\sim 100–500 M_{\odot}$ yr$^{-1}$ are derived when dust extinction is taken into account. The fitting of their multicolor spectral energy distributions indicates stellar masses of $M \gtrsim 10^{11} M_{\odot}$ for most of the galaxies. Their rest-frame UV morphology is highly irregular, suggesting that merging-driven starbursts are going on in these galaxies. Morphologies tend to be more compact in the near-IR, a hint for the possible presence of older stellar populations. Such galaxies are strongly clustered, with seven out of nine belonging to redshift spikes, which indicates a correlation length of $r_s \approx 9–17 h^{-1}$ Mpc ($1 \sigma$ range). Current semianalytical models of galaxy formation appear to underpredict by a large factor ($\gtrsim 30$) the number density of such a population of massive and powerful starburst galaxies at $z \approx 2$. The high masses and SFRs, together with the strong clustering, suggest that at $z \approx 2$ we may have started to explore the major formation epoch of massive early-type galaxies.

Subject headings: cosmology; observations — galaxies: evolution — galaxies: formation — galaxies: high-redshift — galaxies: starburst — large-scale structure of universe

1 INTRODUCTION

The remarkable success of the cold dark matter (CDM) scenario to account for the cold microwave background power spectrum (Bennett et al. 2003) leaves the understanding of galaxy formation and evolution as one of the most compelling, unresolved issues of present cosmology. Semianalytical renditions of the CDM hierarchical paradigm have thus far favored a slow growth with time, with a major fraction of the mass assembly taking place at $z \lesssim 1$ (e.g., Baugh et al. 2003; Somerville, Primack, & Faber 2001), with virtually all massive galaxies disappearing by $z \approx 1.5$. Recent results from the K20 project (Cimatti et al. 2002a, 2002b, 2002c; Daddi et al. 2002; Pozzetti et al. 2003) appear to be at variance with these expectations. The K20 project consists of a spectroscopic survey of $\sim 500$ $K_s < 20$ objects selected over 52 arcmin$^2$ and has revealed a sizable high-redshift tail in the galaxy redshift distribution, where $\sim 30$ galaxies ($\sim 6\%$ of the total sample) were found at $z > 1.7$. Semianalytical CDM models would have predicted no galaxy at all at such high redshifts in the whole sample (see Fig. 4 in Cimatti et al. 2002c). The redshift distribution could be reproduced with pure luminosity evolution (PLE) models, although not for all realizations (see also Somerville et al. 2004). However, for only a few among the $z \gtrsim 1.5$ galaxies was a spectroscopic redshift available, while for all other such galaxies only the photometric redshifts could be obtained. In order to put on firmer grounds such a major result of the K20 project (and to understand the nature of these high-$z$ galaxies), we have conducted new Very Large Telescope (VLT) spectroscopic observations of galaxies with either photometric or (uncertain) spectroscopic redshift above $z \approx 1.7$. This Letter reports the results of the new spectroscopic observations and combines them with the optical Hubble Space Telescope Advanced Camera for Surveys (HST+ACS) and infrared VLT ISAAC imaging made available by the Great Observatories Origins Deep Survey (GOODS) project (Giavalisco et al. 2004). We assume a Salpeter initial mass function, $\Omega_\Lambda, \Omega_m = 0.7, 0.3$, and $h = H_0$ (km s$^{-1}$ Mpc$^{-1}$)/100 = 0.7.

2 THE SPECTROSCOPIC SAMPLE

A sample of 20 galaxies with photometric redshifts $z_{\text{phot}} \gtrsim 1.7$ were selected among the 41 galaxies without spectroscopic redshift identification in the 32 arcmin$^2$ K20 field that is included in the GOODS-South area. The photometric redshifts were improved over an earlier estimate (Cimatti et al. 2002b) by including the ultradepend $HK$ photometry from the GOODS VLT+ISAAC imaging. Within this sample, 10 objects with most secure $z_{\text{phot}}$ have been observed in 2002 November with VLT+FORS2, integrating for 7.2 ks with 0′′6 seeing, and using the 300 V grism covering the range 3600–8000 Å with 13 Å resolution for a 1″ slit.

The spectra were reduced and calibrated in a standard way (Cimatti et al. 2002b) and co-added to already existing spectra, when available. Redshifts were measured for seven galaxies from absorption features in their blue continua identified as UV metal lines (Fig. 1). For the $z > 2$ galaxies, Ly$\alpha$ in absorption and the onset of Ly$\alpha$ forest are also detected. One galaxy (identification [ID] 5) shows He ii λ1640 and C iii] λ1909 emission lines.Hints for those emission lines are also found for object ID 9, for which redshift is less secure because of the faint and noisy spectrum. Together with two previously identified galaxies (IDs 1 and 2), a sample of nine galaxies with spectroscopic redshift $z_{\text{spec}} > 1.7$ is now available among the 304 $K_s < 20$ galaxies in the K20/GOODS-South area (Table 1). Correspondingly, the fraction of
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eq (8) in Daddi et al. 2000a). These densities would increase by
dence level (c.l.). Accounting for cosmic variance due to clustering
calculations). The uncertainties are Poissonian at the 95% confi-

1......1.727 1.74 19.99 1.44 3.15 0.7 26 93 0.3 0.36 0.0 4.6 104 0.2 35 487 0.5 0.50 0.2 25 0.7 5.9 2.0 34.1 3 2.23 2.40 18.72 2.15 4.15 0.0 38 540 0.4 0.0 55 0.4 3.5 3.2 0.25 0.3 6......2.226 2.24 19.94 1.69 3.30 0.4 18 88 0.3 0.71 0.6 0.7 5.5 2.6 0.33 0.5 7......2.227 2.11 19.45 1.80 3.46 1.2 31 178 0.3 0.72 0.13 0.7 5.5 2.2 0.41 1.3 8......2.228 2.43 19.74 2.02 3.66 0.4 26 121 0.3 1.4 17 0.9 7.8 2.1 0.25 0.9 9......2.228 2.29 19.94 1.94 3.65 0.7 30 153 0.3 1.7 26 1.1 9.4 2.7 0.29 1.2

3. PROPERTIES OF K-BAND LUMINOUS GALAXIES AT z ∼ 2

Using the wealth of subsidiary data available on the
GOODS-South area, we investigate in this section the nature
of these K-band luminous galaxies with zspec ∼ 2.

Star formation rates.—The rest-frame UV spectra of these
galaxies indicate that they are actively star-forming. They are
very similar to the template Lyman break galaxy (LBG) spec-
trum (Shapley et al. 2003), and often show Si iv λ1294 ab-
sorption due to OB stars (Fig. 1). Lyα emission is never
detected, as is the case for 25%–50% of LBGs (Shapley et al.
2003), a hint for significant dust extinction. The UV fluxes at
2800 Å correspond to star formation rates (SFRs) in the range
of ∼10–40 M⊙ yr−1 before extinction correction (Kennicutt
1998). The extinction at 1600 Å was estimated from the UV
spectral slope β (Meurer et al. 1999) derived from the multi-
color photometry. The SFRs derived in this way (adopting the
Calzetti et al. 2000 extinction law) are very high, with a median
of ∼400 M⊙ yr−1.

As an alternative estimate HYPERZ was used (Bolzonella
et al. 2000) to fit the Bruzual & Charlot model spectral energy
distributions (SEDs) to the observed ones from the available
deep VLT BVRIJHK photometry, assuming constant SFR
(CSF), and solar metallicity. The best-fitting models require
reddening in the range E(B–V) ∼ 0.3–0.6 and intense SFRs
up to ∼500 M⊙ yr−1, with a median of 150 M⊙ yr−1. Using
an SMC extinction law would lower both the SFRs and
E(B–V) estimates. Interestingly, ID 5 (which has the highest
extinction-corrected SFR) is a faint (soft) X-ray source (XID
563 in the Chandra Deep Field–South catalog; Giacconi et al.
2002). If completely due to star formation, its X-ray luminosity
LX ∼ 2.7 × 1040 ergs s−1 cm−2 corresponds to SFR ∼
500 M⊙ yr−1 (Nandra et al. 2002). The object is also a faint
1.4 GHz radio source with a flux density of 103 ± 13 μJy (K.
Kellermann et al. 2003, private communication), fully consistent
with the tight X-ray–radio luminosities correlation shown by
Ranalli et al. (2003) for actively star-forming galaxies.

We cannot definitively rule out the presence of an obscured
active galactic nucleus (AGN), but the lack of AGN signatures in

TABLE 1

K-BAND LUMINOUS STARBURSTS AT z ∼ 1.7 IN THE K20GOODS AREA

| ID | zspec | zphot | K Vega | J-K Vega | R-K Vega | β' | SFRUV* (M⊙ yr−1) | SFR† (M⊙ yr−1) | E(B-V) | T (Gyr) | M* (1010 M⊙) | rD (arcsec) | rD (kpc) | C* | A* | S* |
|----|-------|-------|--------|---------|---------|----|----------------|----------------|-------|--------|------------|------------|----------|-----|-----|----|
| 1   | 1.727 | 1.74  | 19.99  | 1.44    | 3.15    | -0.7| 26             | 93             | 0.3   | 0.36   | 0.0        | 4.6        | 10^4     | 0.2 | 35 | 487|
| 2   | 1.729 | 2.54  | 19.07  | 1.99    | 4.54    | 0.7 | 13             | 490            | 0.6   | 0.25   | 0.11       | 0.8        | 7.1      | 0.3 | 1.4 | 22 |
| 3   | 1.901 | 1.65  | 19.68  | 1.57    | 3.42    | -0.9| 27             | 155            | 0.3   | 0.52   | 0.79       | 5.4        | 1.9      | 0.41| 0.6 | 22 |
| 4   | 2.060 | 1.78  | 19.31  | 1.83    | 4.15    | -0.2| 35             | 487            | 0.5   | 0.50   | 0.25       | 0.7        | 5.9      | 2.0 | 3.4| 1.3|
| 5   | 2.223 | 2.40  | 18.72  | 2.15    | 4.15    | 0.0 | 38             | 540            | 0.4   | 1.0    | 0.55       | 0.4        | 3.5      | 3.2 | 0.25| 0.3|
| 6   | 2.226 | 2.24  | 19.94  | 1.69    | 3.30    | -0.4| 18             | 88             | 0.3   | 0.71   | 0.60       | 0.7        | 5.5      | 2.6 | 0.33| 0.5|
| 7   | 2.227 | 2.11  | 19.45  | 1.80    | 3.46    | -1.2| 31             | 178            | 0.3   | 0.72   | 0.13       | 0.7        | 5.5      | 2.2 | 0.41| 1.3|
| 8   | 2.228 | 2.43  | 19.74  | 2.02    | 3.66    | 0.4 | 26             | 121            | 0.3   | 1.4    | 17         | 0.9        | 7.8      | 2.1 | 0.25| 0.9|
| 9   | 2.228 | 2.29  | 19.94  | 1.94    | 3.65    | -0.7| 30             | 153            | 0.3   | 1.7    | 26         | 1.1        | 9.4      | 2.7 | 0.29| 1.2|

* UV spectral slope. Typical errors are ±0.1.
† SFR derived from the 2800Å luminosity without extinction correction.
‡ Star formation rate, extinction, luminosity-weighted stellar age, and stellar mass derived from SED fitting of CSF models with reddening.
§ Quantities measured in the F850LP band, typical errors are ΔC, ΔA, ΔS, ∼ 0.15, 0.15, and 0.05.
* The redshift for ID 9 is less secure.
its UV spectrum, showing instead a strong Si iii $\lambda$1294 photo-
spheric absorption line, the nondetection in the Chandra hard band
and the low X-ray–to–optical flux ratio $[\log (f_{15.2\mu m}/f_\text{opt}) \sim
-1.3]$ indicate that this is a vigorous star-forming galaxy. The
stacked X-ray fluxes of the undetected sources give a 2 $\sigma$ detection
corresponding to (SFR) $\approx 100 \ M_\odot \ \text{yr}^{-1}$ ($\Gamma = 2.1$ is assumed
following Brusa et al. 2002). In general, the limits on the X-ray
luminosities ($L_X \lesssim 10^{42} \ \text{ergs} \ \text{cm}^{-2}$) and the low X-ray–to–
optical flux ratios $[\log (f_{15.2\mu m}/f_\text{opt}) \lesssim -1.5]$ imply that our sam-
ple contains virtually no AGNs. The high SFRs qualify these
galaxies as starbursts and allow buildup of the equivalent of a
local $M^* \sim 10^{11} \ M_\odot$ galaxy in 0.2–1 Gyr.

Stellar masses.—Although the SEDs are reddened in the rest-
frame UV, they appear even redder toward the near-IR, where
they show a steep flux increase, starting in the F850LP band
or beyond, which is suggestive of relatively stellar popu-
lations. The CSF models discussed above imply $M_{\text{stellar}} =
(0.3–5.5) \times 10^{11} \ M_\odot$ and luminosity-weighted ages of about
250–1700 Myr. In this case, the near-IR bump is reproduced
by a prominent Balmer break. The CSF models are likely to
underestimate the masses of the galaxies, because older stars,
with higher mass to light ratios, may well be present, and yet
their light would be outshined by the younger ones. In order
to estimate reliable upper limits, the minimal contribution to
the K-band light by the ongoing starburst is determined by
fitting a very young ($\lesssim 10 \ \text{Myr}$) reddened component to the
SEDs between the B and J bands. This component accounts
for 30%–50% of the K-band light. Assuming the remaining K-
band light is due to a maximally old 3 Gyr stellar-population
component, the resulting masses are typically a factor of 2–5
higher than estimated from CSF models, similar to what is
found for LBGs (Papovich et al. 2001).

Clustering.—Significant redshift pairwise is observed among
$z \approx 2$ galaxies, a clear indication of strong clustering. Monte
Carlo simulations are used to constrain the correlation length
$r_0$ from the short-scale pairing, assuming a slope of $\gamma = 1.8
$ for the correlation function (Daddi et al. 2002). A flat selection
function between $z = 1.7$ and 2.25 is used.

Seven independent pairs within 5 $h^{-1}$ comoving Mpc are
found in our sample of nine galaxies, implying $r_0 > 7 \ h^{-1}$ Mpc
comoving (95% c.l.) and a most likely range of 9–17 $h^{-1}$ Mpc
(68% c.l.).

Morphology.—In the HST+ACS and VLT+ISAAC images
taken for the GOODS project, all galaxies show a rather ir-
regular light distribution (Fig. 2), with bright knots and low
surface brightness regions, often split into separated com-
ponents. We measured the CAS parameters (Conselice 2003; Ber-
shady et al. 2000 and references therein), finding relatively
high clumpiness ($S$), high asymmetry ($A$), and very low con-
centration ($C$; see Table 1). As $S$ is known to correlate with
the SFRs, the large $S$-values are consistent with the high SFRs
estimated above. The $A$-values of most galaxies are consistent
within the errors with the limit of $A > 0.35$, typical of galaxies
undergoing merging or that experienced merging in the last
Gyr (Conselice 2003). The low $C$-values are also typical of
local merger-driven starbursts, or ultraluminous infrared gal-
xies. There is a trend for increasing $C$ from the rest-frame far-
UV (F435W band) to the optical (K band, resolution effects
having been taken into account), implying a morphological K-
correction. Also, this is typical of starburst galaxies (see, e.g.,
Dey et al. 1999 and Smail et al. 2003) and may indicate the
presence of an older bulge/disk component (e.g., Labbé et al.
2003a) or a higher reddening in the central regions. All the
galaxies appear rather extended, allowing hosting of the high
estimated SFRs. The average half-light radius is $r_{0.5} = 0.7
$ in the F850LP band, about $0.5 \ \text{kpc}$.

4. RELATING TO OTHER $z \approx 2$ GALAXY POPULATIONS

We now compare the properties of these K-band luminous
galaxies to those of other relevant populations at $z \approx 2$, namely,
LBGs at $z \sim 3$, very red $z \gtrsim 2$ galaxies, and SCUBA sources.
Compared to LBGs (e.g., Giavalisco 2002), these near-IR bright
starbursts at $z \sim 2$ have, on average, larger sizes, higher masses
and SFRs, and stronger clustering. Despite their spectral sim-
ilarity, these galaxies are not just a special subsample of LBGs.
Indeed, it appears that they have redder UV continuum than
the reddest LBG template (Fig. 1). In fact, most objects in
Table 1 have $\beta > -1$, while most LBGs have UV slopes be-
tween $\beta = -2$ and $-1$, and virtually none have $\beta > -0.5
$(Adelberger & Steidel 2000). Hence, the two populations ap-
pear to be only partially overlapping.

These $z \approx 2$ starbursts are red in the near-IR, with
$J-K \gtrsim 1.7$, and their clustering is consistent with that of much
fainter $K < 24$ galaxies at $z > 2$ with $J-K > 1.7$ colors (Daddi
et al. 2003). In fact, van Dokkum et al. (2003) found significant
redshift pairwise among five galaxies at $z > 2$ selected with
$J-K > 2.3$ (Franx et al. 2003; Labbé et al. 2003b). Neverthe-
less, the two samples show different properties, because strong
Ly$\alpha$ emissions, regular morphologies, and AGN signatures
are common among van Dokkum et al. objects. Our nine spectro-
scopically confirmed galaxies have $J-K < 2.3$ and very clumpy
and asymmetric morphologies. We conclude that there is a large

Fig. 2.—ACS (top and center rows for F435W and F850LP, respectively, epochs 1+2+3) and VLT+ISAAC (bottom row for K; seeing 0.5) imaging for the
galaxies with spectroscopic identification. The images are 5$\arcsec$ on a side. Redshift measurement for each galaxy is given in the bottom panels.
variety of properties among $K$-band bright galaxies at $z > 2$, which we are just starting to explore.

Given the estimated SFRs, redshift range, and peculiar morphology, some of our galaxies are potential SCUBA sources (Chapman et al. 2003a, 2003b). Red UV SEDs with $\beta > -0.5$ are indeed common among SCUBA sources (e.g., Dey et al. 1999; Chapman et al. 2002), which also appear to have large clustering (e.g., Webb et al. 2003). Nevertheless, SCUBA sources have much lower spatial density and are often much fainter than $K_s = 20$, while some of our sources may have too low SFRs to be submillimeter-bright. Hence, also in this case the two populations are likely to overlap only partially.

5. DISCUSSION

These $K$-band luminous starbursts provide a substantial contribution to the cosmic SFR density (SFRD) at $z \sim 2$; adding up the SFRs from SED modeling we derive $SFRD_{\text{保守}} \sim 0.04 M_{\odot} \text{yr}^{-1} \text{Mpc}^{-3}$ from the nine spectroscopically confirmed galaxies alone. This estimate is certainly affected by incompleteness, and yet it already represents $\sim 30\%-60\%$ of the SFRD within the range $1.5 < z < 3$ (see, e.g., the compilation by Nandra et al. 2002). These galaxies are also among the most massive systems detected at $z \sim 2$. Six objects in our sample have $M_{\text{stellar}} > 10^{11} M_{\odot}$ (conservative estimates), resulting in a number density of $\sim 10^{-4} \text{Mpc}^{-3}$ and a mass density of $\sim 2 \times 10^{7} M_{\odot} \text{Mpc}^{-3}$, both $\sim 10\%$ of the corresponding local value (Cole et al. 2001). Integrating over the mass function predicted by the Baugh et al. (2003) model at $z = 1.92$, one expects on average only 0.2 galaxies with $M_{\text{stellar}} > 10^{11} M_{\odot}$ within the explored volume and even less if the semianalytical mass function was properly normalized at $z = 0$. Therefore, these semianalytical models underestimate the number of massive galaxies at $z \sim 2$ by a factor of 30 and possibly much more given the incompleteness of our spectroscopic sample. The assembly of massive galaxies apparently took place at a significantly larger redshift (earlier epoch) than predicted by the models (see also Genzel et al. 2003). On the other hand, these $z \sim 2$ galaxies are too actively star-forming and irregular to be consistent with PLE models with high redshift of formation. The agreement between the observed redshift distribution at $z > 1.7$ and the PLE model described in Cimatti et al. (2002c) is therefore likely to be just chance.

These $K$-band luminous starbursts are very strongly clustered, suggesting that they are hosted in very massive and biased environments, which itself argues for these objects being quite massive. At $z < 2$ the only known sources with $r_0 \geq 7 h^{-1}$ Mpc are old, passively evolving extremely red objects (EROs; Daddi et al. 2000a, 2001) and local massive elliptical galaxies (Norberg et al. 2002). These $z \sim 2$ galaxies are therefore likely to evolve into such classes of objects. If star formation ends rapidly, it would take them $\sim 1$ Gyr to develop very red optical to near-IR colors and to morphologically relax to regular bulge-dominated galaxies. This scenario, with massive spheroids still forming at $z \sim 2$, would be in quite good agreement with some properties of $z \sim 1$ old EROs, including their number counts (Daddi, Cimatti, & Renzini 2000b), hints for residual star formation present in their UV rest frame (McCarthy et al. 2001), and with the inferred formation redshifts ($2.4 \pm 0.3$) of their stellar populations (Cimatti et al. 2002a). At the same time, it would predict a paucity of passive EROs at, say, $z > 1.3-1.5$. Finally, we note that a major shift seems to happen for the clustering properties of star-forming galaxies from $z \sim 1$, where they have very low clustering (see, e.g., Daddi et al. 2002), to $z \sim 2$, where they have a very large one. The straightforward interpretation is that while at $z \leq 1$ star formation is mostly confined to low-mass galaxies, and at $z \sim 2$ we are starting to see the major buildup phase of massive early-type galaxies. It remains to be determined whether this $z \sim 2$ activity represents the peak or the low-$z$ tail of the massive spheroid formation epoch. With the existing technology, we should soon be able to answer this question, mapping massive galaxy assembly as a function of both redshift and large-scale structure environment.

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