We report results from a search for massive and evolved galaxies at $z \gtrsim 5$ in the GOODS southern field. Combining HST ACS, VLT ISAAC, and Spitzer IRAC broadband photometric data, we develop a color selection technique to identify candidates for being evolved galaxies at high redshifts. The color selection is primarily based on locating the Balmer break using the K and 3.6 $\mu$m bands. Stellar population synthesis models are fitted to the SEDs of these galaxies to identify the final sample. We find 11 candidates with photometric redshifts in the range $4.9 \lesssim z < 6.5$, dominated by an old stellar population, with ages $0.2-1.0$ Gyr. The stellar masses are in the range $(0.5-5) \times 10^{11} M_\odot$. One candidate has a spectroscopically confirmed redshift, in good agreement with our photometric redshift. The galaxies are very compact, with half-light radii in the observed K band smaller than $\sim 2$ kpc. Seven of the 11 candidates are also detected at 24 $\mu$m with the MIPS instrument on Spitzer. While the observed 24 $\mu$m emission is consistent with an obscured AGN, we define a “no-MIPS” sample of candidates in addition to the full sample. Results will be quoted for both samples. If the stellar mass estimates are correct, the presence of these massive and evolved galaxies when the universe was $\sim 1$ Gyr old could suggest that conversion of baryons into stars proceeded more efficiently in the early universe than it does today.

Subject headings: cosmology: observations — galaxies: evolution — galaxies: formation — galaxies: high-redshift — galaxies: photometry

Online material: color figures

1. INTRODUCTION

An important goal of observational cosmology is to understand how stars are assembled into galaxies and how this is related to the evolution of dark matter halos. In prevailing hierarchical models, star formation starts out in low-mass systems, which build more massive galaxies through sequential merging (e.g., White & Rees 1978; Somerville 2004). In this picture, the most massive galaxies are found at relatively low redshifts. Recently, a significant population of galaxies with stellar mass $\sim 10^{11} M_\odot$ has been found at $z \sim 2-3$ (e.g., Franx et al. 2003; Glazebrook et al. 2004; Fontana et al. 2004; Yan et al. 2004; Daddi et al. 2005b; Rudnick et al. 2006; van Dokkum et al. 2006). Stellar population synthesis models combined with broadband photometric data show that many of these galaxies contain an old stellar population, with ages indicating a star formation phase within $1-3$ Gyr after the big bang. Moreover, a number of submillimeter-detected galaxies at $z \sim 2-3$, which are known to be massive systems, based on their inferred molecular gas and dynamical mass estimates (e.g., Greve et al. 2005), also appear to contain an old stellar population with mass $\sim 10^{11} M_\odot$ (Borys et al. 2005). Therefore, a consensus seems to be emerging, that the most massive galaxies seen today formed the bulk of their stars within the first $\sim 3$ Gyr of cosmic history (e.g., Cimatti et al. 2004; Daddi et al. 2005a; Juneau et al. 2005). However, it is not known how these stars were assembled into their present host galaxies, whether this was done during multiple merger events, as proposed in hierarchical models, or if the stars and their host galaxy are coeval. In view of the early formation epoch implied for many of these massive galaxies, the question whether the formation is hierarchical or monolithic becomes a matter of semantics as the merger timescale becomes comparable to the dynamical timescale.

Recent ultra deep surveys, done at wavelengths stretching from the UV to mid-infrared, have resulted in detection of galaxies and active galactic nuclei (AGNs) at even higher redshifts, reaching into the era of reionization. One example is HUDF-JD2, in the Hubble Ultra Deep Field (HUDF), which Mobasher et al. (2005) identify as a candidate for a massive, evolved galaxy at $z = 6.5$. The age of this galaxy is estimated to be $\gtrsim 600$ Myr, with a stellar mass of $\sim 6 \times 10^{11} M_\odot$, much larger than the stellar mass of the Milky Way. The implied age of this galaxy means that the bulk of the stars were formed on a short timescale just a few million years after the recombination era. Other recent studies have used data from the Spitzer Space Telescope to analyze the stellar masses and ages for galaxies at $z > 5$ (e.g., Yan et al. 2005, 2006; Eyles et al. 2005, 2007; Stark et al. 2007; Verma et al. 2007). The inferred stellar masses are in the range $(1-10) \times 10^{10} M_\odot$, and ages are of several times $10^8$ yr. In several cases, galaxies have spectroscopically determined redshifts. Another spectroscopically confirmed galaxy is the gravitationally lensed object HCM 06 at $z = 6.56$ (Hu et al. 2002), with a stellar mass of a few times $10^{10} M_\odot$, and an age of $\sim 300$ Myr (e.g., Chary et al. 2005; Schaerer & Pelló 2005).

The presence of these massive and old galaxies at $z \gtrsim 5$ holds important clues for understanding how the first galaxies formed and how the galaxy population in general has evolved with cosmic time. In order to determine whether a significant population of massive and old galaxies exists at $z > 5$, and to derive the parameters characterizing this population, we need a selection method that specifically targets and selects evolved stellar systems at very high redshifts, using broadband photometric data available from deep multiwavelength surveys. The presence of old galaxies at high redshift cannot efficiently be inferred using the normal Lyman dropout technique. The dropout technique has...
In this paper we develop a method for selecting galaxies dominated by a stellar population older than $\sim$100 Myr and situated at $z \gtrsim 5$, and we discuss the results and implications. The technique is primarily based on detecting the presence of a well-developed Balmer break, redshifted to $\sim 3 \mu$m, that can be probed by the $K_s - 3.6 \mu$m color index. A second color index is used to further isolate the old high-$z$ galaxies from foreground “contaminants.” The color signature of the Balmer break has previously been used to select galaxies at redshifts $z \sim 1-3$ (Franx et al. 2003; Daddi et al. 2005b; Adelberger et al. 2004). By choosing a suitable filter combination, the Balmer break can be used to select galaxies at any redshift, in a manner similar to the Lyman break technique. In this paper we refer to the galaxies selected through this technique at $z > 5$ as Balmer break galaxies (BBGs).

The paper is structured as follows: In § 2 we present our sample and photometric data. In § 3 we discuss the Balmer break feature and the stellar population synthesis models used and examine the confidence of the model fitting procedure using Monte Carlo simulations. In this section we also discuss degeneracies and define the final color selection criteria used in this paper. In § 4 we present the Balmer break candidates selected using our color criteria and model fits of synthetic stellar spectra. We derive associated physical parameters from the models and discuss the Spitzer MIPS 24 $\mu$m detections. In this section we also discuss the individual sources and assign a confidence classification to each source based on its likelihood to have the correct redshift. In § 5 we apply our model fitting to galaxies with known spectroscopic redshift and assess the reliability of the estimated parameters. In § 6 we discuss different sources of errors and derive the completeness of our sample. We discuss our results in § 7 and compare the number density of BBGs with the expected number density of dark matter halos. In § 8 we give a summary of our results. We adopt $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$ throughout this paper. All magnitudes are in the AB system (Oke 1974).

2. THE CATALOG AND PHOTOMETRIC DATA

The sample used in this study is selected from the Great Observatories Origins Deep Survey (GOODS) southern field (Dickinson et al. 2003b). This field has been observed at many wavelengths, including optical (Hubble Space Telescope [HST] Advanced Camera for Surveys [ACS]; BViz; Giavalisco et al. 2004), near-infrared (VLT ISAAC: JHK$_s$; B. Vandame et al. 2008, in preparation), and deep mid-infrared imaging with the Spitzer Space Telescope with IRAC (3.6, 4.5, 5.7, and 8.0 $\mu$m; M. Dickinson et al. 2008, in preparation) and MIPS (24 $\mu$m; M. Dickinson et al. 2008, in preparation) instruments.

The HST ACS images were obtained in four bands, F435W ($B_{435}$), F606W ($V_{606}$), F775W ($I_{775}$), and F850LP ($Z_{850}$), to limiting sensitivities of 27.8, 27.8, 27.1, and 26.1 AB mag (10 $\sigma$ for an extended source measured over 0.2 arcsec$^2$ aperture), respectively. We use the ESO version 1.5 public release of the GOODS-S ISAAC images. These cover 156 arcmin$^2$ in the J and $K_s$ bands and a somewhat smaller region, 124 arcmin$^2$, in the $H$ band. The ISAAC images have limiting magnitudes of 24.8, 24.2, and 24.1 (10 $\sigma$ for an extended source measured over 1.0$''$ diameter circular aperture), respectively. These data were taken in 0.4$''$ seeing condition. Details about the optical (BViz) and near-IR observations and data reduction are given in Giavalisco et al. (2004). The Spitzer IRAC mid-IR images of the GOODS-S are obtained in all four channels (3.6–8.0 $\mu$m) to 10 $\sigma$ limiting magnitudes for an isolated point source, from 25.8 mag (3.6 $\mu$m) to 23.0 mag (8.0 $\mu$m) (M. Dickinson et al. 2008, in preparation). Fluxes were measured in the MIPS data by fitting point sources to prior positions of objects detected by IRAC, enabling reliable deblending even in moderately crowded conditions (R. Chary et al. 2008, in preparation). The MIPS catalog is 84% complete at the formal 5 $\sigma$ flux density limit (24 $\mu$Jy). In practice, detectability and photometric uncertainty in the IRAC and MIPS data are ultimately a function of image crowding. We visit this issue when discussing the reliability of our candidates.

We block-averaged the ACS images (0.03") to the same scale as that of the ISAAC data (0.15") and convolved them with a Gaussian approximation of the ISAAC point-spread function (PSF). We then generated a source catalog by running SExtractor (Bertin & Arnout 1996) in dual image mode, using the ISAAC $K$ band as the detection image. A $K$-band–selected catalog was then constructed from the PSF-matched ACS (BViz) and ISAAC (JHK$_s$) images, with total magnitudes (corresponding to MAG_AUTO values from SExtractor) measured. Since the accuracy of near-IR photometry is crucial in selecting and exploring the nature of the BBG candidates, we further examine these by performing manual photometry on the ISAAC images of the BBG candidates. The results from the two methods of photometry agree within their respective photometric errors (see also § 4.2). We coordinate-match the $K$-band–detected sources with the weighted sum of channels 1 and 2 from the Spitzer IRAC catalogs, using SExtractor and PSFs appropriate for those channels (M. Dickinson et al. 2008, in preparation). A maximum radial tolerance of 1" was used to match sources between the $K$-band and IRAC catalogs. We have found that matches with larger separations are almost inevitably due to blending of multiple objects in the IRAC images, which perturb the centroid position of the source as well as corrupt the photometry, and are therefore to be avoided.

IRAC photometry was performed by measuring the magnitudes over 3" or 4" circular aperture diameters. These were then converted to total magnitudes using aperture corrections based on Monte Carlo simulations, in which artificial images of compact galaxies (half-light radii $< 0.5$") were added to the IRAC images after convolving by the appropriate PSFs and subsequently recovered by SExtractor. The reason for using two different apertures is the potential for source blending in the IRAC images. Blending may artificially brighten the IRAC magnitude and hence force these sources into the selection range (§ 3.4). We used a 3" aperture when estimating the IRAC photometry for sources that have a nearest neighbor, measured in the $K$ band, within a radius $\lesssim 3.0"$. If the separation was less than 1.5", the source was discarded. For the remaining sources we used a 4" aperture. The corrections to “total” magnitude are obtained from the simulations, as described above, and are larger for the smaller aperture. After selection of the final sample (§ 4.3), we repeated the IRAC photometry through PSF fitting using the GALFIT package (Peng et al. 2002) and used these results in the SED fits. This is discussed further in § 4.2.

The final result is a $K$-band–selected catalog containing total magnitudes in ACS (BViz), ISAAC (JHK$_s$), and IRAC (m$_{3.6}$, m$_{4.5}$, m$_{5.7}$, m$_{8.0}$) bands. We estimate the completeness by fitting a power-law function to the faint end of the differential number counts of the apparent $K$ magnitudes for all galaxies in the $K$-selected catalog (Fig. 1). The catalog is 82% complete at $K_M = 23.5$. This catalog is used to identify candidates satisfying our selection criteria.

3. SELECTION OF HIGH-REDSHIFT CANDIDATES

The selection and identification of evolved galaxies at $z \gtrsim 5$ comprise two steps: (1) selection of likely candidates based on
colors and (2) identification of the most likely old and high-redshift galaxies from these candidates by fitting SEDs from population synthesis models. This two-step process is necessary because, as we show below, the colors of poststarburst galaxies at $z \gtrsim 5$ are to some extent degenerate with dusty star-forming galaxies at the same or lower redshifts.

### 3.1. The Balmer Break

One feature in the spectral energy distribution (SED) of galaxies that can be used to identify poststarburst galaxies at both high and low redshift is the Balmer break. The Balmer break at 3648 Å is an age-dependent diagnostic of the stellar population. The break is most prominent in A stars (in O and B stars, the hydrogen is mostly ionized, while in cooler late-type stars, the opacity is dominated by H$^-$, with a maximum opacity at 8500 Å). For a single generation of stars, the break is most pronounced for ages between 0.1 and 1.0 Gyr. However, the development of the Balmer break occurs for stellar populations in both passively evolving and continuous star formation scenarios, but on different timescales. For an instantaneous starburst, followed by passive evolution, the break develops as the O and B stars leave the main sequence, and for continuous star formation, when the number of O stars has reached a more or less constant value while the number of A stars is still increasing (e.g., Leitherer et al. 1999). The Balmer break has the potential to resolve the age-extinction degeneracy. Most extinction laws have a relatively smooth dependence on wavelength and will not produce the steplike feature of the Balmer break. Its usefulness, however, is limited by the photometric accuracy relative to the amplitude of the 3648 Å break.

In this paper we concentrate on galaxies at $z \gtrsim 5$. For redshifts in the range $z \approx 5$–9, the Balmer break is located between the $K$ and 3.6 μm passbands. In this redshift range, observed optical wavelengths correspond to the extreme-UV region, which is mostly lost, through the Lyman break, interstellar and intergalactic absorption. This means that the selection of $z \gtrsim 5$ galaxies is greatly aided by using observed near- and mid-infrared wavelengths. Such selection criteria have only become possible with the availability of relatively deep imaging with the IRAC instrument on Spitzer.

### 3.2. Stellar Population Synthesis Models

Stellar population synthesis models will be used for two purposes. First, the models are used to define regions in color-color plots that are the likely location of $z \gtrsim 5$ poststarburst candidates. This is done by defining a limited set of parameters characterizing this type of galaxy and following their color evolution as a function of redshift. Secondly, the models are used to fit the observed broadband photometric data of the color-selected candidates. Apart from providing global galaxy parameters, such as redshift, age, and stellar mass, this will allow a clear distinction between the type of galaxies in which we are interested and interlopers of various kinds.

We use the stellar population synthesis models of Bruzual & Charlot (2003, hereafter BC03) to explore the broadband color evolution of galaxies with different star formation histories, ages, and metallicities. In order to fit the SED of each galaxy in an unbiased and prior-free manner, we explore a large parameter space for redshift, stellar age, extinction, metallicity, and star formation history. While hidden priors cannot be avoided due to the cutoffs in parameter values, as well as the form assumed for the star formation history, we strive to keep these to a minimum. The number of parameters used to define the SED is ultimately limited by the number of photometric data points.

We use a Salpeter initial mass function (IMF) with lower and upper mass cutoffs at 0.1 and 100 $M_\odot$, respectively. The resulting SEDs are redshifted in the range $z = 0.2$–8.6 with $\Delta z = 0.1$, and their colors are evaluated in fixed observed bands (ACS: $BViz$; VLT ISAAC: $JHKs$; Spitzer IRAC: $3.6, 4.5, 5.7, 8.0 \mu m$). We do not include longer wavelength MIPS data in the fitting process as the BC03 models do not include dust or PAH emission. Dust obscuration is parameterized using the attenuation law of Calzetti et al. (2000). It is parameterized through the $E_{B-V}$ color index, covering the range $E_{B-V} = 0.0$–0.95, with $\Delta E_{B-V} = 0.025$. Additional attenuation is introduced through neutral hydrogen absorption in the intergalactic medium (IGM). We used the Madau (1995) prescription for the mean IGM opacity. The age of a stellar population is measured from the onset of star formation. We adopt simple monotonous star formation histories, as with the present photometric data we cannot quantitatively assess the goodness of fit for models with multiple previous bursts of star formation. Although this may influence the estimates of the average stellar age, obscuration, and total stellar mass, it does not substantially affect the overall shape of the SED. Since the photometric redshift is based on distinct features in the SED, it is a robust estimate regardless of the stellar populations considered. The age range extends from 5 Myr to 2.4 Gyr, with steps of 5 Myr up to 100 Myr, followed by age steps of 100 Myr up to 2.4 Gyr. The maximum age corresponds to the age of the universe at $z \approx 2.7$. Four different metallicities are used, 0.2, 0.4, 1.0, and 2.5 $Z_\odot$. The star formation history is parameterized as an exponentially decreasing star formation rate (SFR), where $\tau$ represents the e-folding decay time. We use $\tau = 0.0, 0.1, 0.2, 0.3, 0.4, 0.6, 0.8$, and 1.0 Gyr. The $\tau = 0$ case represents an instantaneous starburst.

A large number of models ($\approx 2.5 \times 10^6$) are precomputed, spanning the parameter space as defined above. The resulting SEDs are integrated through the appropriate filter response functions. We

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5 As shown in Papovich et al. (2006), models that incorporate multiple bursts of star formation may result in larger derived stellar masses.
also derive a bolometric luminosity by integrating over the entire wavelength range. Finding the best-fit parameters for a given set of photometric data points then involves normalization to the observed fluxes and calculation of the goodness of fit for each point in parameter space. The best-fit model parameters are selected from the model resulting in the minimum \( \chi^2 \). Since a \( \chi^2 \) value is derived for all parameter combinations, the confidence of the fit can easily be evaluated. The SED fitting is done using flux densities \( f_\nu \). The treatment of observed upper limits needs special consideration. The model SEDs have extremely steep flux density gradients at wavelengths shorter than 1216 Å and have essentially zero flux below the Lyman limit at 912 Å. If the redshift is high enough to shift the Lyman limit to wavelengths redder than a given filter, the observed upper limit becomes useless as the difference between the upper limit flux density and that given by the model can amount to several orders of magnitude. On the other hand, if the redshift is low enough to place the filters with upper flux limits on the red side of the Lyman limit, the upper limit has a more meaningful role in constraining the model fit. Due to the large difference between the observed flux limits and the model flux for high-redshift objects, where the Lyman limit is on the red side of the upper limit, the \( \chi^2 \) estimate will invariably favor a lower \( z \) solution, but with a very poor fit at both short and long wavelengths and a correspondingly large \( \chi^2 \) value. This introduces a bias, which we overcome by not including the upper limits in the \( \chi^2 \) estimate whenever the model SED is fainter than the upper limit. However, when the flux of the model SED is larger than the observed upper limit, thus violating an observed constraint, we include this in the \( \chi^2 \) estimate.

3.3. Monte Carlo Simulations

With a limited set of photometric data points, it is necessary to keep the number of model parameters to a minimum in order to achieve a meaningful goodness-of-fit estimate. In addition, degeneracies between some of the parameters, such as stellar age, extinction, and metallicity, exist and can potentially lead to a large area of parameter space where a good fit between the model and the observed data points can be found. One way out of this dilemma is to apply priors, where we assume certain properties of the galaxies being fitted. While this can lead to a “sharper” solution, it also carries the potential of introducing biases. We have chosen to keep the priors to a minimum (§3.2) and accept a somewhat more diffuse solution space for a few cases, but keeping the solutions as unbiased as possible.

In order to define the confidence and test the stability of the model fitting and the resulting solution space, we performed Monte Carlo simulations, where the fluxes in all photometric bands are allowed to vary simultaneously within their nominal errors. The errors are assumed to be normally distributed and uncorrelated. While these assumptions are only partly true, due to sensitivity limits and zero-point uncertainties in the photometry, they represent a good approximation to the true photometric uncertainty. The resulting distribution of the best-fit values for each parameter represents the probability distribution for this particular parameter. As seen below, a small percentage of the Monte Carlo realizations result in a best fit at a lower redshift. The actual fit of these solutions can be good but represents an unlikely combination of the observed photometric data values, given their errors.

We generate \( 10^3 \) realizations of the photometric data set for each galaxy. In each realization we allow each photometric data point to vary stochastically as described above. The bands with nondetections are still treated as upper limits. We then determine the best-fit parameters for each realization of the photometric data in the same manner as described in §3.2. The resulting distribution of redshift, age, stellar mass, extinction, etc. for the \( 10^3 \) Monte Carlo realizations allows an estimate of the confidence of the various solutions. This gives a more accurate estimate of the confidence than a single realization and the corresponding variation in the \( \chi^2 \) values.

3.4. The Color Selection Technique

We are primarily interested in galaxies with a well-defined Balmer break, i.e., with ages >0.2 Gyr, and situated at redshifts \( z \gtrsim 5 \). Hence, the primary color parameter is the \( K_s - 3.6 \mu m \) color, which straddles the 3648 Å Balmer break at \( 5 < z < 9 \) (see §3.1).

There are several physical parameters that can cause red colors in a stellar population, including the age of the stellar population, metallicity, and dust extinction. Because of this degeneracy, a single color is usually not a robust indicator of redshift, nor does it distinguish between different galaxy types, for instance, an obscured star-forming galaxy, a poststarburst galaxy, and an elliptical galaxy. This is illustrated in Figure 2, where we show the SED for a typical poststarburst (red line) and a dusty starburst galaxy (blue line) for a variety of age, metallicity, and \( E_{B-V} \) parameters. The model galaxies are placed at \( z = 6.0 \), except in one case where the dusty starburst is located at \( z = 2.5 \). In addition to the SEDs, we also show the ISAAC JHK, and the IRAC 3.6 \( \mu m \) bandpasses. All the SEDs are normalized at 3.6 \( \mu m \). In Figure 2a, both the poststarburst and dusty starburst are at \( z = 6.0 \), and both have solar metallicity, with the only difference being their age (600 Myr vs. 5 Myr) and the extinction \( E_{B-V} \) (0.0 vs. 0.5). In this case, the SED of the poststarburst galaxy has a larger gradient at wavelengths shorter than the Balmer break compared to the dusty starburst. Therefore, in this case it is possible to distinguish between these two galaxy types by using a second color index. However, in Figures 2b and 2c we demonstrate the effect when relatively small changes to the galaxy parameters are incorporated. In Figure 2b the metallicity of the poststarburst galaxy is decreased to 0.2 Z\(_{\odot}\), resulting in a somewhat less steep SED gradient shortward of the Balmer break. In Figure 2c, in addition to the lower metallicity of the poststarburst galaxy, the \( E_{B-V} \) of the dusty starburst increased to 0.7. In this case, the dusty starburst galaxy has a steeper gradient shortward of the Balmer break than the poststarburst. Finally, in Figure 2d we keep the parameters the same as in Figure 2c but move the dusty starburst galaxy to \( z = 2.5 \). The SEDs in Figure 2 show that, in general, even the use of two color indices may not be sufficient to distinguish between poststarburst and dusty starburst galaxies. It is, however, possible to identify and remove elliptical galaxies from the sample. While the \( K_s - 3.6 \mu m \) color index is the main parameter used for selecting poststarburst galaxies at \( z \gtrsim 5 \), the number of interlopers can be minimized by using a second color index. In this paper we explore the use of the \( J - K_s \) and \( H - 3.6 \mu m \) colors as a secondary index.

In order to better understand the behavior of different types of galaxy models when using two color indices, and to explore their limitations, we constructed synthetic galaxy SEDs for a set of poststarburst, dusty starburst, and elliptical galaxies using the BC03 models. The models explore a wide range of parameter combinations appropriate for each galaxy type (see Table 1). Broadband photometric data were obtained by convolving the SEDs with the appropriate filter response functions. In Figures 3 and 4 we show the resulting tracks when each galaxy model, for a fixed set of parameters, is shifted to different redshifts. For the poststarburst and dusty starburst models, the redshift ranges from \( z = 1 \) to 8. Tracks at \( z < 1 \) do not overlap the ones at higher
redshift and have been omitted from the figures. Each track is marked with a green and blue square, corresponding to $z = 5$ and 8, respectively. The elliptical models are restricted to the range $z = 1–4$, with the green and blue squares marking $z = 2$ and 4.

Using the poststarburst tracks, and limiting the redshift to $5 < z < 8$, we can define a region on the color-color plane that contains all of the model tracks. This is done for both the $J - K$ versus $K_s - 3.6 \, \mu m$ and $H - 3.6 \, \mu m$ versus $K_s - 3.6 \, \mu m$ indices (regions A and B; Figs. 3 and 4, respectively). While the tracks for elliptical galaxies fall well outside the regions defining the poststarburst tracks, this is not the case for dusty starburst galaxies, which occupy a region overlapping with the poststarburst galaxies. The best way of separating these types is to introduce more constraints by fitting the SEDs over the entire wavelength range available and select poststarburst galaxies based on their respective model parameters.

The expected location of poststarburst galaxies on the $J - K$ versus $K_s - 3.6 \, \mu m$ plane is defined by (see Fig. 3; region A)

$$J - K < -1.94 + 3.14(K_s - 3.6 \, \mu m),$$
$$J - K > -1.90 + 1.27(K_s - 3.6 \, \mu m),$$
$$J - K > 1.71 - 0.82(K_s - 3.6 \, \mu m).$$

For the case of $H - 3.6 \, \mu m$ versus $K_s - 3.6 \, \mu m$, the region of interest is defined as (see Fig. 4; region B)

$$H - 3.6 \, \mu m > 1.75, \quad K_s - 3.6 \, \mu m > 1.20.$$

4. RESULTS

4.1. The Balmer Break Candidates

We select $z \geq 5$ candidates from our $K_s$-selected catalog using the color-color diagrams shown in Figure 5. In order to limit the number of selected sources, we also required them to be undetected in the $B$ band, with $m(B_{115}) > 27.85$. At $z > 4.3$, the 912 Å Lyman limit redshifts entirely redward of the ACS F435W filter bandpass, and this requirement lowers the number of foreground objects included in the selection.\footnote{In a few cases the catalog value for the $B$ band would be less than 27.8, but with an uncertainty $>1.0$ mag. If this was the case, we regarded it as an upper limit.}

We call the selection based on the $J - K$ versus $K_s - 3.6 \, \mu m$ colors region A and that based on $H - 3.6 \, \mu m$ versus $K_s - 3.6 \, \mu m$ colors region B. As noted in §2, we also require that the ISAAC and IRAC centroid positions do not differ by more than 1.0”.
find that larger offsets inevitably indicate problems with blending in the IRAC data. On the other hand, there are small, residual astrometric distortions in the current public data products for both the ISAAC and IRAC GOODS images at levels of up to 0.4′′, which make it impractical to adopt much smaller matching tolerances. In the final selection, the center positions of the ISAAC and IRAC sources generally agree to better than 0.5′′, although there are two exceptions (BBG 3361, 0.6′′, and BBG 2068, 1.0′′; see Table 4 below).

Regions A and B contain 112 and 60 sources, respectively. As noted in §2, the ISAAC H-band images cover a smaller solid angle (124 arcmin2) than those at J and Ks (159 arcmin2), which partially accounts for the smaller number of sources in color region B. There are 38 objects that are common to the two color selection regions. The previously identified J-band dropout galaxy, JD2, found in the HUDF by Mobasher et al. (2005), is contained in both regions A and B (BBG 3179).

Fitting BC03 models to all sources in regions A and B shows that nine from region A and eight from region B have photometric redshifts $z > 5$ and ages $>0.2$ Gyr. Four of the high-redshift candidates are common to both regions. The remaining sources in regions A and B have best-fit solutions consistent with dust-obscured starburst galaxies at redshifts $z \approx 1$–3 or dusty post-starburst galaxies at $z < 4$.

Combining sources in regions A and B, which include the previously detected source HUDF-JD2 (BBG 3179), we have a sample of 13 high-redshift Balmer break candidates. The coordinates and photometric data of the 13 candidates found here are given in Table 2 (the data for BBG 3179/JD2 are taken from Mobasher et al. 2005; but see caption to Table 2 for a revision of the photometry).

In Figures 6–15 we show the ACS ($BViz$), ISAAC ($JHK_s$), and Spitzer IRAC images of the 12 new $z \geq 5$ candidates (for the corresponding plots for BBG 3179/JD2, we refer to Mobasher et al. 2005). The results from fitting BC03 models are also shown in Figures 6–15. The photometric data and the best-fit model SEDs from BC03 are shown in the top left panel. The top right panel shows the distribution of $\chi^2_\nu$ values as a function of extinction and redshift when all other parameters are left free to vary at each $(z, E_{B-V})$ point. A wide spread of $\chi^2_\nu$ values is indicative of a degenerate or unstable solution. Finally, the bottom left and right panels show the result from 105 Monte Carlo realizations for the distribution of photometric redshift and stellar mass, respectively. Results for BBG 3179 (HUDF-JD2) can be found in Mobasher et al. (2005).

### 4.2. Effect of Photometric Errors

A major issue with the results obtained in this study is the presence of large photometric errors in fluxes of individual galaxies, which could significantly alter the shape of their SEDs and their estimated parameters. This becomes more serious as we combine observations from different telescopes and instruments with very different characteristics. In this subsection we summarize the steps we take to verify the photometry (e.g., §2) and to study the effect of photometric errors on selection and photometry of our final BBG candidates.

The photometric errors affect our results in two ways. First, they could lead to erroneous inclusion of objects into the BBG sample, or exclusion of some potential candidates. Second, they could affect the observed SEDs and, hence, the final sample and their estimated parameters. Since our technique mainly relies on the size of the Balmer break at $5 \leq z \leq 7$, (i.e., the $K_s - m_{3.6}$

### Table 1

| Model Galaxy         | Age (Gyr) | $E_{B-V}$ | $\tau$ (Gyr) | $Z$ ($Z_\odot$) | Redshift Range |
|----------------------|-----------|-----------|--------------|-----------------|----------------|
| Poststarburst.........| 0.3–1.0   | 0.0–0.2   | 0.0          | 0.2–2.5         | 1–8            |
| Dusty starburst...... | 0.005–0.030 | 0.4–0.7   | 0.0–0.2      | 0.2–2.5         | 1–8            |
| Elliptical............| 1.0–2.4   | 0.0       | 0.0          | 0.4–1.0         | 1–4            |

Fig. 3.—Tracks of three different types of model galaxies in the $J - K$ and $K_s - 3.6 \mu$m color plane. The model tracks represent a range of parameters in $E_{B-V}$, age, and star formation history, characteristic for poststarburst, dusty starburst, and elliptical galaxies. The ranges of the parameters are given in Table 1. Each track starts at $z = 1$ and extends to $z = 8$, with green squares representing $z = 5$ and blue squares $z = 8$, except for the elliptical galaxies where the corresponding redshifts are $z = 2$ and 4. The region inside the wedge outlined by the dashed red line corresponds to region A, where we expect to find $z > 5$ poststarburst galaxies (BBGs).
colors), an examination of the ISAAC and Spitzer photometry is crucial.

The large size of the IRAC PSF could lead to blending in some of our sources. The effect of this is to brighten the IRAC magnitudes, leading to redder $K - m_{3.6}$ colors and false inclusion of a galaxy into the BBG sample. We attempt to correct for this using a smaller ($3''$) aperture for sources with a nearest neighbor in the $K$ band of $<3''$, and then using the appropriate corrections to convert these to “total” magnitude (see §2). We then repeated IRAC photometry on our final BBG candidates by simultaneously modeling the light distribution of the BBG and the galaxies close to it, letting the positions of the galaxies be part of the fit. The IRAC PSF is slightly asymmetric, and we used empirically derived PSFs (from star) for each separate IRAC band and each observing epoch. Application of the GALFIT routine successfully separates the flux contributions of neighboring sources and the Balmer break candidate in all but one case (see below). This procedure was carried out on all the candidates and for all four IRAC bands, resulting in a set of independent total magnitudes.

As the Spitzer observations were done in two different epochs, with different PSFs, we measured the “unblended” magnitudes separately for both epochs. No attempt was made to subtract extended emission by fitting a Sérsic profile. In most cases the BBG candidate and the surrounding neighbors are small enough to allow a simple PSF fitting to estimate the total flux.

Figure 16 and Table 3 compare the IRAC total magnitudes and those estimated using the GALFIT routine. In general, GALFIT magnitudes are fainter. However, for the isolated sources, the two magnitudes agree within 0.05 mag, giving support to our initial IRAC photometry. For the sources where the magnitude difference...
### TABLE 2
**Photometric Data for z > 5 Candidates**

| ID     | R.A.      | Decl. | $B$   | $V$   | $i$       | $z$       | $J$           | $H$           | $K_s$      | 3.6 $\mu$m | 4.5 $\mu$m | 5.7 $\mu$m | 8.0 $\mu$m | 24 $\mu$m$^a$ |
|--------|-----------|-------|-------|-------|-----------|-----------|---------------|---------------|------------|------------|------------|------------|------------|------------|--------------|
| 547.....| 03 32 24.73 | –27 42 44.3 | >27.80 | >27.80 | 27.23 ± 0.84 | 25.67 ± 0.27 | >25.50 | 25.68 ± 0.3 | 24.14 ± 0.28 | 23.21 ± 0.10 | 22.98 ± 0.10 | 22.67 ± 0.16 | 22.42 ± 0.15 | <24 |
| 2068.....| 03 32 26.78 | –27 46 04.2 | >27.8 | >27.8 | 27.02 ± 0.62 | 25.92 ± 0.29 | >24.55 | 25.10 ± 0.43 | 24.89 ± 0.28 | 23.01 ± 0.10 | 22.80 ± 0.10 | 22.03 ± 0.10 | 21.78 ± 0.15 | 22 ± 4 |
| 2864.....| 03 32 53.25 | –27 47 51.6 | >27.8 | >27.8 | >27.1 | >26.60 | >24.55 | 25.82 ± 0.65 | 24.68 ± 0.30 | 22.49 ± 0.10 | 22.02 ± 0.10 | 21.75 ± 0.10 | 21.60 ± 0.15 | 32 ± 6 |
| 2910.....| 03 32 30.27 | –27 47 58.2 | >27.80 | >27.80 | 26.47 ± 0.48 | 26.01 ± 0.38 | 24.84 ± 0.36 | 24.84 ± 0.46 | 23.84 ± 0.14 | 22.73 ± 0.10 | 22.43 ± 0.10 | 22.27 ± 0.10 | 22.45 ± 0.15 | 69 ± 5 |
| 3179.....| 03 32 38.74 | –27 48 39.9 | >29.83 | >30.26 | >30.07 | >29.44 | 27.02 ± 0.32 | 24.94 ± 0.07 | 23.95 ± 0.13 | 22.09 ± 0.10 | 21.80 ± 0.10 | 21.60 ± 0.10 | 21.38 ± 0.15 | 51 ± 10 |
| 3348.....| 03 32 17.22 | –27 49 08.0 | >27.80 | >27.80 | >27.10 | 25.42 ± 0.24 | 24.45 ± 0.17 | 23.83 ± 0.16 | 22.92 ± 0.06 | 21.56 ± 0.10 | 21.23 ± 0.10 | 21.24 ± 0.19 | 21.42 ± 0.15 | 83 ± 4 |
| 3361.....| 03 32 29.97 | –27 49 09.0 | >27.80 | 27.95 ± 0.65 | 26.33 ± 0.30 | 25.81 ± 0.23 | >24.55 | 25.83 ± 0.63 | 24.72 ± 0.22 | 23.46 ± 0.10 | 23.42 ± 0.10 | 23.37 ± 0.18 | 23.01 ± 0.15 | <27 |
| 4034.....| 03 32 10.22 | –27 50 27.8 | >27.80 | >27.80 | 26.88 ± 0.84 | 25.23 ± 0.25 | 24.57 ± 0.18 | 24.04 ± 0.22 | 24.01 ± 0.17 | 22.94 ± 0.10 | 23.04 ± 0.10 | 22.98 ± 0.16 | 23.20 ± 0.19 | <34 |
| 4053.....| 03 32 33.48 | –27 50 30.0 | >27.80 | >27.80 | 25.99 ± 0.21 | 25.44 ± 0.17 | >25.5 | 25.48 ± 0.54 | 24.97 ± 0.33 | 23.73 ± 0.10 | 23.93 ± 0.10 | 23.78 ± 0.19 | 23.36 ± 0.26 | ... |
| 4071.....| 03 32 27.07 | –27 50 31.4 | >27.80 | >27.80 | >27.10 | 27.21 ± 0.92 | 25.58 ± 0.35 | 24.60 ± 0.24 | 24.06 ± 0.14 | 22.63 ± 0.10 | 22.31 ± 0.10 | 22.25 ± 0.10 | 22.11 ± 0.15 | <26 |
| 4135.....| 03 32 48.43 | –27 50 39.0 | >27.80 | >27.80 | >27.1 | 25.80 ± 0.34 | 25.90 ± 0.46 | ... | 24.34 ± 0.27 | 23.14 ± 0.10 | 22.74 ± 0.10 | 22.38 ± 0.16 | 22.24 ± 0.15 | 42 ± 3 |
| 4550.....| 03 32 24.62 | –27 51 38.2 | >27.80 | 27.35 ± 0.44 | 26.05 ± 0.27 | 26.42 ± 0.54 | >25.50 | ... | 24.75 ± 0.27 | 22.82 ± 0.10 | 22.58 ± 0.10 | 22.25 ± 0.10 | 21.67 ± 0.15 | 20 ± 4 |
| 5197.....| 03 32 18.91 | –27 53 02.5 | >27.80 | 27.70 ± 0.45 | 25.22 ± 0.10 | 24.51 ± 0.08 | 24.77 ± 0.13 | 24.68 ± 0.20 | 24.30 ± 0.16 | 22.72 ± 0.10 | 22.64 ± 0.10 | 23.44 ± 0.49 | 23.06 ± 0.23 | <25 |

**Note.** Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

$^a$ MIPS 24 $\mu$m flux density in mJy. All other entries in the table are AB magnitudes: $m_{AB} = -2.5 \log f_\nu + 8.90$. Upper limits are 5 $\sigma$.

$^b$ Marginal MIPS 24 $\mu$m detection: flux $\sim 5 \sigma$.

$^c$ BBG 3179 = JD2. The magnitudes given here are updated from the Mobasher et al. (2005) HUDF values ($J$ 4.5). The GOODS data directly from the $K$-selected catalog are ($BV$): >27.8, 26.83 ± 0.26, 26.58 ± 0.43, 26.00 ± 0.30; ($JHK$): >24.5, 24.24 ± 0.28, 24.29 ± 0.25; (IRAC channels 1, 2, 3, 4): 22.09 ± 0.10, 21.80 ± 0.10, 21.60 ± 0.10, 21.38 ± 0.15.

$^d$ Nondetection in MIPS 24 $\mu$m, but lacks upper limit.
is $0.1$, the GALFIT results suggest that blending is an issue (see Table 3). To explore the impact of this on the model fitting results, we refitted the same BC03 models as before using the revised IRAC fluxes from GALFIT. The only significant change in the parameters defining the best-fit parameters was found for BBG 4034, which now has a best-fit solution as a dusty starburst galaxy at $z = 5.5$ and is therefore disqualified as a BBG. For BBG 4053, which has the largest correction to the IRAC magnitudes, the GALFIT results did not converge satisfactorily due to nearby extended neighbors. Although its best-fit solution is still that of a BBG-type object, we remove it from the sample as well. We discuss the individual galaxies in §4.5. Our final results for all Balmer break candidates, including the Monte Carlo simulations, are based on the magnitudes estimated using the GALFIT procedure.

We examined the ISAAC near-IR magnitudes by performing multiaperture photometry and estimating the total $JHK_s$ magnitudes using individual growth curves. The effect of sky subtraction was examined by performing different methods to independently measure and subtract the background. The estimated total magnitudes from growth curves agree well with MAG_AUTO estimates, independently measured from SExtractor (using background maps). We find an agreement better than 0.05 ($J$), 0.07 ($H$), and 0.09 mag ($K_s$). Furthermore, for the HUDF (a subarea of the GOODS-S), where both ISAAC and NICMOS $JH$ magnitudes are available, we compared these magnitudes for objects in common (Mobasher & Riess 2005) between the two instruments. The agreement was $< 0.05$ at the bright end and $< 0.10$ at the faint end.

It is always possible that combined uncertainties in the ISAAC and IRAC zero points, or some other (presently unknown) effects in their respective photometry, could lead to artificially red $K_s - m_{3.6}$ colors and, hence, erroneous selection of the BBGs or wrong estimates of their physical parameters. We investigate this in §5 by analyzing other, confirmed high-redshift galaxies in the GOODS-S field, comparing their spectroscopic redshifts to photometric redshifts derived in the same way as we have done for the BBGs, using ACS, ISAAC, and IRAC photometry taken from the same catalogs.

### 4.3. Parameters of the Candidates

The final sample of Balmer break candidates with robust IRAC photometry consists of 11 objects. The best-fit parameters resulting from stellar population model fits to the photometry for these objects are presented in Table 4. Here we also present parameter values calculated from the best-fit model parameters: bolometric luminosity, stellar mass, and the initial, current, and average SFRs. As the star formation history is imposed by us and may not reflect...
the actual chain of events, the values given in the table should be viewed as indicative rather than absolute.

In Table 5 we present the median values of parameters obtained from the Monte Carlo simulations. The median values are, in most cases, not very different from those obtained directly from the best-fit model fits using the photometry given in Table 4, except that the median values for metallicities tend to be higher. Overall, the metallicity is the least robust parameter obtained from the model fits. In Table 5 we also list the percentage of Monte Carlo realizations that result in a photometric redshift $z > 4$ and $z > 5$. These values are indicative of the dispersion of the photometric redshifts obtained from the Monte Carlo simulations and, hence, of the stability of the solutions. In Tables 2 and 5 we have removed BBG 4034 and BBG 4053 due to potential blending in the IRAC bands (see §4.2).

The $\chi^2$ value for the best-fit SED is $\leq 2$ for 10 of our 11 candidates. The worst $\chi^2$ value (4.5) is found for BBG 5197, which is the only galaxy in our sample with a spectroscopically determined redshift ($z_{\text{spec}} = 5.552; z_{\text{phot}} = 5.2$; Vanzella et al. 2006). The high $\chi^2$ value is mainly due to one deviating IRAC photometric data point: 5.8 $\mu$m appears to be too faint relative to the rest of the IRAC data points. This cannot be caused by an emission line, and the cause for the deviation remains undetermined. The confidence level in the redshift can also be evaluated from the distribution of $\chi^2$ values as a function of redshift and $E_{B-V}$, as well as from the Monte Carlo simulations. A lower confidence of the photometric redshift is indicated by (1) uncertain photometry caused by source confusion in the IRAC bands, (2) a large dispersion of the redshift distribution from the Monte Carlo simulation, and (3) the existence of a strong bimodal solution (i.e., low $z$, high extinction vs. high $z$, low extinction). In fact, for BBG 5197, the Monte Carlo simulations indicate a stable photometric redshift distribution despite having the worst $\chi^2$ value. A possible reason for a high $\chi^2$ value is the presence of an AGN component and strong emission lines, for which the current SED models are not suitable. Since only one of our final candidates is detected in X-rays (BBG 3348; see below), this does not appear to be a major problem.

Inspection of the results from the Monte Carlo simulations (Figs. 6–15) shows that a generic feature of the Balmer break candidates is the presence of two local $\chi^2$ minima: (1) $z \gtrsim 5$ with little or no dust obscuration, and (2) $z \approx 2$ with $E_{B-V} \approx 0.5–0.9$. This reflects the well-known degeneracy between age, extinction, and redshift. This degeneracy is discussed in §3.4 and illustrated in Figure 2. The secondary minimum at lower redshift is usually interpreted as a dusty starburst galaxy. However, a large part (~40%) of the lower redshift solutions corresponds to galaxies characterized by an old stellar population (elliptical galaxy) with a considerable amount of dust extinction, and not a dusty starburst galaxy per se.
The star formation history is modeled as exponentially declining with a time constant $\tau$. Except for two objects, the candidate galaxies have a current level of star formation activity that is less than 5% of the peak SFR. The candidates with the highest ongoing SFR relative to the peak activity are BBG 2068 (29%) and BBG 4550 (12%). In Table 4 we list the initial, current ($t = t_{SB}$), and average SFRs for the candidate galaxies. For those cases that are best fitted by an instantaneous star formation episode ($\tau = 0$) we arbitrarily assumed that the initial star formation activity is spread over 100 Myr. It is worth keeping in mind that the SFRs discussed here are dependent on the assumed parameterization of the star formation history. The most robust estimate is the average rate, i.e., the stellar mass divided by the age of the stars. The stellar ages range from $1 \times 10^8$ to $1 \times 10^9$ yr, with corresponding formation redshifts $z_{form} = 6$–26 (see Table 4).

The metallicity is not strongly constrained by the solutions. This is due to the degeneracy between metallicity and age, as well as extinction. A change in the metallicity can be offset by a small change in either age and/or extinction. This is evident in the Monte Carlo simulations, where metallicity rarely shows a strongly preferred value. We tried fitting the model SED keeping the metallicity at solar. The results were not significantly different from when using all four metallicity values in the fit.

We measured the half-light radii, $r_h$, of the Balmer break candidates by applying 16 apertures of increasing radius to each galaxy and estimating the encircled flux. The smallest radii were of similar size as the radius of the PSF. We measured $r_h$ on the $K_s$ images, obtained with VLT ISAAC, with a PSF FWHM of $\approx 0.4''$. We derived the half-light radius in 13 of the BBG candidates (plus JD2). In a few cases the growth curves did not turn over at the largest radii. This is most likely due to blending with nearby sources. All of the BBGs with measured $r_h$ are resolved, with an average half-light radius of $0.34'' \pm 0.04''$. However, since the light profiles were not deconvolved with the PSF, they represent upper limits to the half-light radius $r_h$. At a redshift $z = 5.2$, this corresponds to a radius of $\approx 2$ kpc.

The GOODS-S field has been observed at radio wavelengths (1.4 GHz) to a limiting sensitivity of $14$ Jy using the Australian Compact Telescope Array (Afonso et al. 2006). A total of 64 radio sources are found within the GOODS-S field, but none are associated with our Balmer break candidates. Only one of the BBGs in our sample is detected in the 1 Ms X-ray survey of the GOODS-S field done with the Chandra X-Ray Observatory (Giacconi et al. 2002). The galaxy BBG 3348 is undetected in both the soft (0.5–2 keV) and hard (2–8 keV) bands but is marginally detected when combining the two bands. The flux is $9.6 \times 10^{-17}$ ergs s$^{-1}$ cm$^{-2}$. At a redshift $z_{phot} = 5.1$, this translates into $L_X = 3 \times 10^{43}$ ergs s$^{-1}$ ($7 \times 10^9 L_\odot$). This is more than 2 orders of magnitude larger than the typical X-ray luminosity of Lyman break galaxies (LBGs) at $z \approx 3$ and $z \approx 4$ (Lehmer et al. 2005). The X-ray
luminosity of BBG 3348 is only \( \sim 0.2\% \) of the bolometric luminosity derived from the UV-to-IR part of the SED. While this X-ray luminosity is too low for a QSO, it is consistent with the presence of a low-luminosity AGN. The observed X-ray flux probes rest-frame energies in the range \( 3 \lesssim \gamma \lesssim 49 \) keV, where attenuation due to a large hydrogen column density should be a negligible effect. The remainder of the BBGs are undetected with Chandra, with typical \( \lesssim 10^{17} \) and \( \lesssim 10^{16} \) ergs s\(^{-1}\) cm\(^{-2}\) in the soft and hard bands, respectively.

### 4.4. MIPS 24 μm Detections

The GOODS-S field has also been surveyed using the Multiband Imaging Photometer for Spitzer (MIPS) at 24 μm (M. Dickinson et al. 2008, in preparation; R. Chary et al. 2008, in preparation). For galaxies at redshifts \( z \sim 2 \), the MIPS 24 μm band probes a region in the mid-IR corresponding to redshifted PAH emission. For galaxies in the redshift range \( z \approx 5 \), the MIPS band covers rest frame 3–4 μm where emission features from PAHs are weaker. Furthermore, PAH emission is associated with star formation activity, as well as the presence of gas and dust, and since the \( z > 5 \) models that fit the photometry in general have a low level of ongoing star formation and dust, we do not expect to find strong MIPS emission for the Balmer break candidates.

The MIPS 24 μm fluxes are given in Table 2. Among the 11 candidates, 7 show emission at 24 μm. One of the MIPS-detected BBGs is also a weak X-ray source (BBG 3348). The flux densities range from 20 to 83 μJy, with a median value of 42 μJy. The 24 μm catalog (R. Chary et al. 2008, in preparation) fits point sources to the MIPS image at prior positions defined by the IRAC catalog. Therefore, each IRAC source has a 24 μm flux measurement and uncertainty, even if there is no significant detection. We therefore associate the \( K \)-detected galaxies and MIPS 24 μm sources based solely on positional coincidence, where we assume that objects are associated if their centers are located within a radius of 1.0′.

Applying the same selection criterion for the entire \( K \)-selected catalog and requiring that the sources are detected at 24 μm with \( S/N \gtrsim 5 \), we find that for \( K \) magnitudes in the range 20–22, the MIPS 24 μm detection fraction is close to constant at \( \sim 55\% \), while for \( K = 23.5 \), the detection fraction decreases to \( \sim 30\% \). Hence, based on magnitude alone, we would expect to find approximately three BBGs with MIPS 24 μm detection with \( S/N \gtrsim 5 \). Instead, we find \( \sim 55\% \) of the BBGs detected at 24 μm, the same as the detection fraction of the brighter galaxies at \( K \approx 20–22 \).

In Figure 17 we compare the observed 24 μm properties of the galaxies in the \( K \)-selected sample with those of the MIPS-detected Balmer break candidates, as well as a small sample of dusty star-forming galaxies at \( z \approx 2–3 \) (references in the figure caption). Also shown in Figure 17 are LBGs at \( z \approx 3 \), AGNs at \( z \approx 4.5–6 \), and submillimeter-detected galaxies at \( z \approx 2 \). While the BBGs are fainter than the comparison objects, their flux ratios are roughly
similar to both $z \sim 3$ star-forming galaxies and $z \sim 5$ AGNs. We also note that all MIPS-detected BBGs have solutions that include a substantial amount of internal extinction. In general, $E_{B-V} > 0.2$ for the MIPS-detected galaxies, while it is negligible for the non-MIPS galaxies. There are two exceptions: BBG 3348, which has a strong 24 $\mu$m emission but zero extinction in the best model fit (this particular galaxy is the only one detected in X-rays), and BBG 3179 (JD2), which is the BBG with the highest redshift.

The high detection rate among the Balmer break candidates is surprising given the low levels of star formation activity implied by the SED fits (e.g., Table 4). The galaxy HUDF-JD2 at $z_{\text{phot}} \approx 6.5$ is also detected at 24 $\mu$m, and in Mobasher et al. (2005) it was shown that this emission can be consistent with the presence of an obscured AGN. The SED associated with such an AGN has a minimal impact on the part of the SED covered by the ACS/ISAAC/IRAC bands. While the presence of a supermassive black hole in the BBGs would be expected if they follow the local correlation between stellar and black hole mass (Magorrian et al. 1998; Gebhardt et al. 2000), the prevalence of relatively strong 24 $\mu$m emission in the Balmer break candidates and the lack of X-ray emission remains a challenge and concern for the BBGs. In the following we discuss two scenarios for the BBGs: (1) all 11 candidates are considered as real, and (2) only the four candidates without detectable 24 $\mu$m emission will be considered as likely candidates (BBG 547, BBG 3361, BBG 4071, BBG 5197). The latter defines the "no-MIPS" sample. Two of the MIPS-detected BBGs are only detected at the $\sim 5 \sigma$ level (BBG 2068 and BBG 4550) but are considered as MIPS detected in the following.

4.5. Individual Sources

BBG 0547.—This is an isolated source. It is not detected at MIPS 24 $\mu$m. The Monte Carlo simulations give 67% probability for being at $z > 5$ (94% for being at $z > 4$). The SED fit is good, except that the $K$-band flux is off by a substantial amount.

BBG 2068.—This source has a neighbor 2.2" away. The two sources appear well separated, and the GALFIT procedure converges satisfactorily. The Monte Carlo simulations, however, give $\sim 90\%$ probability for this source to be at $z > 5$. The internal extinction is high, with $E_{B-V} = 0.3$. It is detected in the MIPS 24 $\mu$m band with S/N $\approx 5$ and a coordinate offset $\sim 1"$. The MIPS detection is therefore uncertain.

BBG 2864.—This is an isolated source, clearly seen in the IRAC bands, and is detected in the MIPS 24 $\mu$m band. It is detected in the ISAAC $K$ band and marginally in the $H$ band. It remains undetected in the $B$ and $J$ bands. The model SED represents an excellent fit, with a substantial amount of internal extinction ($E_{B-V} = 0.25$). The Monte Carlo simulations, however, give a very broad redshift distribution with a $68\%$ probability of $z > 5$ and $77\%$ probability of $z > 4$. The reason for the broad distribution is that the source is poorly constrained due to the upper limits.
BBG 2910.—This is an isolated source, with the nearest neighbor at a distance of 3.0 arcsec. Nevertheless, since the neighbor is a relatively bright foreground object, GALFIT photometry gives corrected IRAC magnitudes. The Monte Carlo simulations imply a 16% probability of \( z > 5 \) and 67% probability of \( z > 4 \), consistent with the best-fit redshift of \( z = 4.9 \) and a relatively narrow redshift distribution. The source is detected in the MIPS 24 \( \mu \)m band.

BBG 3179.—This object is detected by MIPS at 24 \( \mu \)m. This object is also known as HUDF-JD2 and discussed in Mobasher et al. (2005). It is situated 2700 arcsec from a foreground galaxy. In the HUDF, JD2 is undetected in all four ACS bands at AB magnitudes \( k \geq 30 \) (see Table 2). However, in our K-selected catalog, based on the shallower GOODS data, it is flagged as a tentative detection in the \( Viz \) bands. Using the latter photometry results in a photometric redshift \( z = 5.1 \), a stellar mass of \( 5 \times 10^{11} M_\odot \), and an age for the stellar population of 2 Gyr. This age is well in excess of the age of the universe, and BBG 3179 is the only candidate in our sample that violates the cosmological age restriction. The SED fit has a \( \chi^2 \approx 5 \), and the Monte Carlo simulations give a wide redshift distribution. Inspection of the UDF ACS/NICMOS images reveals that BBG 3179 is surrounded by several faint neighboring galaxies, affecting the aperture-based flux estimates. Careful subtraction of the neighbors was done on the UDF data (Mobasher et al. 2005), leading to upper limits to all four ACS bands and a photometric redshift \( z = 6.5 \). While the stellar mass in this case is comparable to what we find using the GOODS data, the age is found to be 0.6–1.0 Gyr. In the remainder of this work we base the JD2 results on the UDF data. A recent analysis of this galaxy by Dunlop et al. (2007) gives the same results as found in Mobasher et al. (2005) when using the same photometric data. In addition, Dunlop et al. (2007) make an independent assessment of the ACS data where JD2 is assumed detected in the \( Viz \) bands (albeit well below 3 \( \sigma \)), at levels \( \approx 0.8 \) mag brighter than in the Mobasher et al. (2005) analysis of the HUDF data. With this set of ACS photometric data, Dunlop et al. (2007) find a best-fit photometric redshift \( z_{\text{phot}} = 2.2 \).

BBG 3348.—This is an isolated source, detected in the MIPS 24 \( \mu \)m band. The best-fit redshift is \( z = 5.1 \), and the Monte Carlo simulations give a 33% probability for \( z > 5 \) and 67% for \( z > 4 \), consistent with the best-fit redshift. This is the only Balmer break.

7 The upper limits to the ACS magnitudes used here are slightly modified compared to those presented in Mobasher et al. (2005). In the latter analysis of the HUDF ACS data an aperture of diameter 0.48" was used to estimate the photometry, while an aperture of 0.9" was assumed and quoted in the text. A reanalysis of the ACS data, using the correct aperture diameter of 0.9", masking the faint neighbors and remeasuring the background noise amplitude, results in slightly brighter limits to the ACS magnitudes of JD2. The corrected upper limits are given in Table 2. These modified upper limits have no effect on the parameters defining the best-fit SED or the stellar mass. However, for the Monte Carlo simulations, the fraction of realizations with \( z_{\text{phot}} > 5 \) decreases from 85% to 76%. The NICMOS, ISAAC, and IRAC photometries are not affected by this.
candidate detected with Chandra. The X-ray luminosity is $3 \times 10^{43}$ ergs s$^{-1}$, constituting only $\sim 0.2\%$ of the bolometric luminosity.

**BBG 3361.**—This is an isolated source; there is no MIPS 24 $\mu$m detection. The Monte Carlo simulations give a 51% probability for $z > 5$ and 100% for $z > 4$, which is consistent with the best-fit solution $z_{\text{phot}} = 5.0$ and a small redshift dispersion.

**BBG 4071.**—This is an isolated source, not detected in the MIPS 24 $\mu$m band. The Monte Carlo simulations give a redshift distribution with 51% of the realizations at $z > 5$ and 62% at $z > 4$. The dispersion of redshifts above $z = 4$ is, however, large, with median redshift of 5.1. The model SED fits well, except for the $H$ band.

**BBG 4135.**—This is an isolated source with a detection in the MIPS 24 $\mu$m band. The redshift distribution from the Monte Carlo simulations is fairly broad, with 35% of the realizations at $z > 5$ and 71% at $z > 4$, consistent with the implied redshift $z = 4.9$. The model fits suggest a fairly large amount of internal extinction ($E_{B-V} = 0.35$).

**BBG 4550.**—There is a relatively bright neighbor at a distance of $\sim 2^\prime$. BBG 4550 is increasingly becoming brighter in the IRAC bands. The model SED represents a fairly good fit, with some internal extinction ($E_{B-V} = 0.150$). The source is detected in the MIPS 24 $\mu$m band. The Monte Carlo simulations give a redshift distribution with 22% at $z > 5$ and 79% at $z > 4$. The relatively low probability for $z > 5$ is to be expected as the best-fit redshift is $z = 4.9$.

**BBG 5197.**—This source is spectroscopically confirmed at $z = 5.552$ (Vanzella et al. 2006). The best fit and the median photometric redshift are both $z = 5.2$. It is an isolated source with no MIPS 24 $\mu$m detection. The Monte Carlo simulations give a 93% probability of the source being at $z > 5$ ($\sim 100\%$ for $z > 4$). The model SED indicates no internal extinction. The fit, however, is not perfect for the IRAC bands. This is probably caused by a deviating $m_{5.8}$ photometric data point. The Monte Carlo simulations give a very narrow redshift distribution.

5. THE BALMER BREAK TECHNIQUE APPLIED TO OTHER HIGH-$z$ GALAXY SAMPLES

The high-redshift Balmer break candidates provide a formidable challenge to spectroscopy. They are very faint at both optical and near-infrared wavelengths, and the low level of ongoing star formation means that strong emission lines, like Ly$\alpha$, will be weak or nonexistent. Nevertheless, one of the Balmer break candidates is spectroscopically confirmed. We discuss this particular galaxy in more detail below.

An alternate way to test the reliability of the parameters derived from the SED fitting technique, in particular the photometric redshift, is to apply the models to galaxies with confirmed spectroscopic redshifts, observed with the same, or similar, filter combinations as we use for the BBG candidates in this paper. These galaxies will inevitably be brighter and/or more actively star-forming, but they will provide a concrete test of the procedures.
We applied the Balmer break sample. We constructed a sample of galaxies with spectroscopic redshifts from several sources. The ESO/GOODS program of spectroscopy of galaxies in the GOODS-S field has resulted in 807 optical spectra of 652 individual objects (Vanzella et al. 2006). From this survey we obtained 394 galaxies with securely determined spectroscopic redshifts. These galaxies have redshifts in the range $z = 0.2 - 4.5$ and are observed with the same telescope and filter combination as our BBG sample. There is very good agreement between photometric and spectroscopic redshifts in general (Fig. 18). An exception is a group of nine outliers, for which the photometric redshifts are higher than the spectroscopic ones. The reason for this discrepancy is partly due to crowding, which makes both spectroscopy and photometry difficult. In addition, most of the deviant sources have a dual redshift solution, with a low redshift of slightly higher than the high-redshift solution. Since we do not apply any priors to the photometric redshift determination, the solution with the lowest $\chi^2$ is always chosen. The scatter for $(z_{\text{spec}} - z_{\text{phot}})/(1 + z_{\text{spec}})$ has $\sigma = 0.12$ for all 394 galaxies. Excluding the deviant sources, the scatter is $\sigma = 0.06$. The inset in Figure 18 shows the $(z_{\text{spec}} - z_{\text{phot}})/(1 + z_{\text{spec}})$ as a function of redshift.

We analyzed the spectroscopically confirmed galaxies from Yan et al. (2005) and Eyles et al. (2005), using the same code as used for our BBGs. As input we used the published photometry and changed the filter response functions as necessary. We kept the redshift as a free parameter, despite a known $z_{\text{spec}}$. The resulting photometric redshifts agree well with the spectroscopic ones (see Table 6), with differences typically less than $|\Delta z| = |z_{\text{spec}} - z_{\text{phot}}| < 0.2$ (one exception is object 15 in Yan et al. [2005], where $z_{\text{spec}} = 5.50$ and we obtained $z_{\text{phot}} = 4.8$).

Both Yan et al. (2005) and Eyles et al. (2005) fitted BC03 model SEDs to some of their galaxies (Table 6). The best-fit models imply stellar masses of a few times $10^{10} M_\odot$ and ages of...
a few times $10^8$ yr with small amounts of extinction. Metallicity, which is less well constrained than the other parameters, is mostly consistent with solar metallicity. In our model fits, we find parameter values that are very close to those obtained by both Yan et al. (2005) and Eyles et al. (2005). The values derived by us are compared to the published values in Table 6.

We also fitted a model SED to the lensed galaxy HCM 6A, with a confirmed spectroscopic redshift $z = 6.56$ (Hu et al. 2002; see also Chary et al. 2005; Schaerer & Pello 2005; Egami et al. 2005). Keeping the redshift as a free parameter, we derive a photometric redshift of $z = 6.66$ with a stellar population age of $\sim 300$ Myr. The stellar mass of HCM 6A, corrected for magnification due to lensing, is $\sim 4 \times 10^9 M_{\odot}$. This is an actively star-forming galaxy, and H$\alpha$ emission may introduce flux in the 4.5 $\mu$m IRAC band (e.g., Chary et al. 2005). While this may introduce an error in the mass and age estimates, the photometric redshift is not influenced.

Among the galaxies observed in the ESO/GOODS program of spectroscopy of galaxies in the GOODS-S field (Vanzella et al. 2006) is the Balmer break candidate BBG 5197 (GDS J033218.92–275302.7). A strong emission line with an asymmetric profile where the blue side is cut off is identified as Ly$\alpha$ at $z_{\text{spec}} = 5.54$. Our photometric redshift for this source is $z_{\text{phot}} = 5.2$. This is the only source from our Balmer break sample that is part of the ESO/GOODS spectroscopic survey. A second line is seen at $\lambda_{\text{obs}} = 972$ nm, consistent with the N $\text{iv}$] $\lambda 1483$ line at the same redshift. The N $\text{iv}$] emission line is not ordinarily detected in star-forming galaxies, but it is seen in AGNs, where it is usually accompanied by N $\text{v}$ $\lambda 1240$. Fosbury et al. (2003) discuss an object at $z = 3.36$ with similar UV emission lines, which they interpret as a low-metallicity, low-mass, primeval galaxy with gas ionized by extremely hot, young stars. It seems contradictory that a galaxy with an apparently massive, mature stellar population implied by model fits to photometry for BBG 5197 would have such properties, but conceivably the active star formation may apply to only a small fraction of the stellar mass, perhaps related to relatively pristine gas in some component merging with the more massive, mature host galaxy. Alternatively, some unusual AGN may be responsible for the atypical UV emission line ratios, but this cannot easily explain the apparent presence of a well-developed Balmer break discontinuity in the SED of this galaxy.

Recently Stark et al. (2007) studied a sample of $z$-band–selected galaxies containing both star-forming and quiescent galaxies, restricted to $z \sim 5$. Spectroscopic redshifts for 14 of these galaxies had previously been obtained by Vanzella et al. (2006) as part of a larger spectroscopic survey of the GOODS-S field. The 14 galaxies have an average redshift $\bar{z} = 4.92$. One of the galaxies observed by Vanzella et al. (2006), and included in the Stark et al. (2007) sample, is also part of our Balmer break sample, BBG 5197 (ID GDS J033218.92–275302.7 in Vanzella et al. 2006; ID 32_8020 in Stark et al. 2007). Two additional galaxies with spectroscopic redshifts (IDs 33_10388 and 33_10340) have...
properties similar to the BBGs (see Table 6) but fall just outside our color selection regions. This suggests that they are similar to our poststarburst galaxies, but at a redshift $z < 5$. Indeed, these objects turn out to have spectroscopic redshifts $z_{\text{spec}} = 4.50$ and 4.44, compared to our photometric redshifts of $z_{\text{phot}} = 4.6$ and 4.7, respectively. These two galaxies are part of our $K_s$-selected sample, and although they have properties consistent with them being massive poststarburst systems, they were excluded from our sample due to their lower redshifts. Nevertheless, the good agreement between their spectroscopic and photometric redshifts lends support to the derived photometric redshifts for the rest of the BBGs.

In a recent paper Dunlop et al. (2007) present a search for massive galaxies at $z > 4$ using a version of the GOODS-S catalog similar to the one used here, including Spitzer IRAC data. Instead of using a color selection, they fitted BC03 models to all galaxies in their sample and found 19 candidates with $z_{\text{phot}} > 4$. After further refinement of the photometry, they selected a final sample of six galaxies. Their conclusion was that all of these were dusty and old galaxies at $z \sim 2$. None of the objects in the Dunlop sample are part of our BBG sample, and it would be interesting to explore the reason for this. The selection by Dunlop et al. (2007) was done on objects with $K_s < 23.5$ (AB magnitudes). Only one of the original 13 BBGs in our sample has a $K$ magnitude as bright as this (BBG 3348, the only BBG with an X-ray detection). While this explains why our BBGs are not part
of Dunlop’s sample, it does not exclude Dunlop’s sources to be part of our sample. All of the Dunlop et al. (2007) galaxies are present in our $K$-selected catalog of 5754 galaxies. We identified Dunlop’s 19 objects with implied $z_{\mathrm{phot}} > 4$ in our catalog and put them through the same selection and fitting routine as for the BBGs. We immediately discard 4 of the 19 galaxies due to a positional offset between the ISAAC and IRAC centroids in excess of 2″. Such a large offset strongly suggests that the IRAC sources are blended with nearby neighbors and that the IRAC photometry is unreliable. Of the remaining 15 galaxies, 9 objects fall in our color selection regions ($\S$ 3.4), including five of the six galaxies in Dunlop’s revised sample. Of the nine galaxies fulfilling our color selection, the best-fit parameters (obtained using the photometric values and errors from our catalog) show that seven have $z_{\mathrm{phot}} \leq 2.5$. For the remaining two galaxies (Dunlop IDs 2957 and 2958) we find $z_{\mathrm{phot}} = 4.6$ and 4.8, respectively. One of these (ID 2957) has a very uncertain $z_{\mathrm{phot}}$, where the Monte Carlo simulations give equal probability for a $z \approx 4.5$ and $z \approx 2.0$ solution. For the other source, ID 2958, our results agree well with those of Dunlop et al. (2007), and it represents a good fit ($\chi^2 = 1.03$). The implied stellar mass is very large ($9 \times 10^{11} M_\odot$). However, we do not find any galaxy in the Dunlop et al. (2007) sample that satisfies our redshift cutoff $z \geq 5$.

To summarize, our model fitting recovers known spectroscopic redshifts with a reasonably high degree of accuracy for galaxies at both low and high redshifts. The parameters derived by us for $z > 5$ galaxies agree with those obtained by other groups. We interpret this as an indication that our technique is robust and reliable when applied to the Balmer break sample as a whole.

6. SYSTEMATIC ERRORS AND COMPLETENESS

6.1. Effects of Potential Systematic Errors

There are several sources of potential systematic errors that could affect our results. Foremost is the reliability of the derived photometric redshifts. With only one BBG spectroscopically confirmed, we have to use indirect methods to assess the confidence of the redshift estimates for the remainder of the candidates. The photometric redshift technique was tested in the previous section ($\S$ 5), where we showed that the photometric redshifts obtained from our fitting technique are robust, with an estimated success rate of about 90%. Hence, assuming that the derived redshifts are approximately correct, we need to consider other effects that could potentially lead to erroneous parameter values. Here we are most concerned with parameters essential for estimates of the stellar mass.

### TABLE 3

| ID       | $m_{\mathrm{total}}$ | $m_{\mathrm{GALFIT}}$ | $\Delta m^a$ | $m_{\mathrm{total}}$ | $m_{\mathrm{GALFIT}}$ | $\Delta m^a$ | $m_{\mathrm{total}}$ | $m_{\mathrm{GALFIT}}$ | $\Delta m^a$ | $m_{\mathrm{total}}$ | $m_{\mathrm{GALFIT}}$ | $\Delta m^a$ |
|----------|---------------------|----------------------|--------------|---------------------|----------------------|--------------|---------------------|----------------------|--------------|---------------------|----------------------|--------------|
| 547....... | 23.17               | 23.21                | 0.04         | 22.98               | 22.98                | 0.00         | 22.76               | 22.69                | -0.07        | 22.18               | 22.42                | 0.24         |
| 2068........ | 22.71               | 23.01                | 0.30         | 22.58               | 22.80                | 0.22         | 22.02               | 22.03                | 0.01         | 21.88               | 21.78                | -0.09        |
| 2864........ | 22.47               | 22.49                | 0.03         | 22.06               | 22.02                | -0.03        | 21.70               | 21.75                | 0.05         | 21.55               | 21.60                | 0.05         |
| 2910........ | 22.61               | 22.73                | 0.12         | 22.38               | 22.43                | 0.05         | 21.15               | 22.27                | 0.12         | 22.24               | 22.45                | 0.21         |
| 3348........ | 21.52               | 21.56                | 0.04         | 21.20               | 21.23                | 0.03         | 21.19               | 21.24                | 0.09         | 21.29               | 21.42                | 0.13         |
| 3361........ | 23.45               | 23.46                | 0.01         | 23.38               | 23.42                | 0.04         | 23.28               | 23.37                | 0.09         | 22.95               | 23.01                | 0.06         |
| 4034\(b\) | 22.72               | 22.94                | 0.22         | 22.75               | 23.04                | 0.29         | 22.79               | 22.98                | 0.19         | 22.84               | 23.20                | 0.36         |
| 4053\(b\) | 23.22               | 23.73                | 0.51         | 23.33               | 23.93                | 0.60         | 23.09               | 23.78                | 0.69         | 23.26               | 23.36                | 0.10         |
| 4071........ | 22.50               | 22.63                | 0.13         | 22.25               | 22.31                | 0.06         | 22.18               | 22.25                | 0.07         | 22.01               | 22.11                | 0.10         |
| 4135........ | 23.09               | 23.14                | 0.05         | 22.71               | 22.74                | 0.03         | 22.34               | 22.38                | 0.03         | 22.22               | 22.42                | 0.02         |
| 4550........ | 22.67               | 22.82                | 0.14         | 22.48               | 22.58                | 0.10         | 22.02               | 22.25                | 0.23         | 21.46               | 21.67                | 0.21         |
| 5197........ | 22.73               | 22.72                | -0.01        | 22.68               | 22.64                | -0.04        | 23.98               | 23.44                | -0.54        | 23.05               | 23.06                | 0.01         |

Notes.—BBG 3179 (HUDF-JD2) was not included here. IRAC photometry was taken from Mobasher et al. (2005).

\(a\) $\Delta m = m_{\mathrm{GALFIT}} - m_{\mathrm{total}}$

\(b\) Removed from the sample due to large corrections to the IRAC magnitudes (see $\S$ 4.2).
In Mobasher et al. (2005) we used both the BC03 and Starburst99 (SB99; Leitherer et al. 1999; Vázquez & Leitherer 2005) models on the galaxy HUDF-JD2 and found them to give essentially identical results when using the same parameterization of the star formation history. However, in a recent paper, Maraston (2005) presented stellar synthesis models that include a greater contribution to the red optical and near-infrared light from thermally pulsating asymptotic giant branch (AGB) stars for stellar populations of ages a few hundred Myr and older, compared to models such as BC03 and SB99. For a given age, the Maraston models result in a smaller $M/L$ ratio than the BC03 and SB99 models. The difference becomes significant for wavelengths $k_{1}/C^{2}2$ m. The effect of the redder SED on fitting broadband photometric data including near-infrared and IRAC bands can be significant for redshifts $z < 4$, while for higher redshifts, the difference in the model SEDs is most pronounced in the longest wavelength IRAC bands. Nevertheless, the smaller $M/L$ ratio when using the Maraston models instead of BC03 or SB99 on stellar populations of ages from a few hundred Myr to $C^{2}1$ Gyr, i.e., the range of ages considered for the BBG sample, could result in lower estimated stellar masses due to the increased near-infrared flux from AGB stars for a given stellar composition.

![Fig. 17.—The 24 μm MIPS data for galaxies in the $K$-selected catalog, matched to the MIPS catalog. The top panel shows the distribution of 24 μm fluxes (μJy) for 1327 sources with a positional coincidence with MIPS 24 μm sources of $\leq 1.0''$. The bottom panel shows the flux density ratio $f_{24}/f_{5.6}$ vs. the $f_{24}$ for the 1327 sources (small dots). In addition, we also show the seven BBGs detected at 24 μm (crosses), a sample of $z \sim 3$ LBGs (filled circles; Rigopoulou et al. 2006), AGNs at redshift $z \sim 4.5$–6 (filled triangles; Hines et al. 2006; Jiang et al. 2006), and submillimeter-detected galaxies (open circles; Ashby et al. 2006). [See the electronic edition of the Journal for a color version of this figure.]

![Fig. 18.—Comparison between spectroscopic and photometric redshifts for galaxies in the GOODS-S field (394) shown as filled circles. The 25 additional high-redshift objects for which spectroscopic redshifts are known, and listed in Table 6, are shown as stars. The inset shows the distribution of $(z_{\text{spec}} - z_{\text{phot}})/(1 + z_{\text{phot}})$ as a function of redshift. [See the electronic edition of the Journal for a color version of this figure.]}

### Table 5: Median Values from Monte Carlo Simulations for the Final Sample of $z > 5$ Balmer Break Candidates

| ID    | $z$ | $z_{\text{phot}} > 4$ | $z_{\text{phot}} > 5$ | $E_{B-V}$ | $t_{\text{SF}}$ (Gyr) | $Z$ | $\log M_*$ ($M_\odot$) | $z_{\text{spec}}$ | Comments                  |
|-------|-----|-----------------------|-----------------------|----------|------------------------|----|------------------------|-------------------|--------------------------|
| 0547  | 5.4 | 95.1                  | 67.3                  | 0.100    | 0.8                    | 0.4 | 2.5                    | 11.010            | 15                       |
| 2068  | 5.2 | 98.0                  | 89.8                  | 0.325    | 0.9                    | 0.4 | 2.5                    | 11.354            | 17                       |
| 2864  | 6.0 | 77.3                  | 68.2                  | 0.150    | 0.8                    | 0.0 | 1.0                    | 11.649            | 24                       |
| 2910  | 4.8 | 67.4                  | 15.5                  | 0.425    | 0.1                    | 0.0 | 0.4                    | 10.913            | 5                        |
| 3179a | 6.5 | 85.1                  | 85.1                  | 0.000    | 0.5                    | 0.0 | 1.0                    | 11.667            | 13                       |
| 3348  | 5.0 | 66.6                  | 32.9                  | 0.025    | 0.7                    | 0.1 | 0.2                    | 11.543            | 10                       |
| 3361  | 5.1 | 99.6                  | 51.3                  | 0.000    | 0.8                    | 0.3 | 1.0                    | 10.756            | 12                       |
| 4071  | 5.1 | 62.4                  | 51.2                  | 0.250    | 0.2                    | 0.0 | 1.0                    | 11.121            | 6                        |
| 4135  | 4.7 | 70.8                  | 34.6                  | 0.375    | 0.2                    | 0.8 | 0.4                    | 10.924            | 6                        |
| 4550  | 4.8 | 79.4                  | 22.2                  | 0.150    | 1.0                    | 0.2 | 2.5                    | 11.239            | 16                       |
| 5197  | 5.2 | 99.5                  | 93.2                  | 0.000    | 0.9                    | 0.3 | 0.2                    | 10.896            | 17                       |

* The JD2 (BBG 3179) results are based on Monte Carlo simulation using photometric data from the HUDF (see § 4.5; Mobasher et al. 2005).
We use a Salpeter IMF with a lower and upper mass cutoff at 0.1 and 100 $M_\odot$, respectively. Changing the lower mass cutoff to $1 M_\odot$, or using an IMF that is deficient in lower mass stars relative to a Salpeter IMF, such as the IMF proposed by Chabrier (2003), would reduce the inferred stellar masses by a factor of 2 or more. It is, however, worth noting that the use of a Salpeter IMF with the upper and lower mass cutoffs as used here would not substantially change our masses relative to those of other galaxies at similar or lower redshifts as long as the IMF remains independent of redshift and galaxy mass.

It is presently difficult to estimate the combined effect of these potential systematic errors. The effects of changing the IMF to a more top-heavy one and using the intrinsically redder SED from the Maraston models would both be to lower the average stellar masses of the BBGs. The magnitude of the effect is unknown but could possibly be a factor of 2 or more.

### TABLE 6

Comparison of Spectroscopic and Photometric Redshifts for Sources with $z_{\text{spec}} > 4$

| Galaxy   | $z_{\text{phot}}$ | $z_{\text{spec}}$ | Age (Gyr) | $\tau$ (Gyr) | $\log M_*/(M_\odot)$ | Note       |
|----------|-------------------|-------------------|-----------|--------------|-----------------------|------------|
| Yan 1    | 5.7               | 0.0               | 1.0       | 1.0          | 0.2                   | 10.29      | Our result |
| Yan 4    | 4.8               | 0.025             | 0.1       | 0.2          | 0.2                   | 8.99       | Our result |
| Yan 5    | 5.8               | 0.0               | 1.0       | 0.4          | 0.2                   | 10.35      | Our result |
| Yan 6    | 4.5               | 0.0               | 0.4       | 0.4          | 0.2                   | 9.91       | Our result |
| Yan 7    | 4.5               | 0.0               | 0.7       | 1.0          | 0.2                   | 9.81       | Our result |
| Yan 15   | 4.8               | 0.10              | 0.035     | 0.0          | 0.2                   | 9.58       | Our result |
| Yan 5    | 5.4               | 0.0               | 0.015     | 0.0          | 1.0                   | 8.87       | Our result |
| Yan 6    | 5.25              | 0.0               | 0.143     | 0.07         | 1.0                   | 9.32       | Our result |
| Yan 7    | 0.8               | 0.3               | 0.2       | 0.0          | 2.5                   | 9.02       | Our result |
| GLARE 3001 | 5.7                 | 0.175             | 0.010     | 0.0          | 1.0                   | 9.32       | Our result |
| GLARE 3001 | 5.7                 | 0.175             | 0.010     | 0.0          | 1.0                   | 9.32       | Our result |

Note:

- Stellar mass is corrected for magnification due to lensing by a factor of 4.5.
- The IDs are from Stark et al. (2007), redshifts from Vanzella et al. (2006). 
- Uncertain spectroscopic redshift (Vanzella et al. 2006).
- Stellar mass is corrected for magnification due to lensing by a factor of 4.5.

We use a Salpeter IMF with a lower and upper mass cutoff at 0.1 and 100 $M_\odot$, respectively. Changing the lower mass cutoff to $1 M_\odot$, or using an IMF that is deficient in lower mass stars relative to a Salpeter IMF, such as the IMF proposed by Chabrier (2003), would reduce the inferred stellar masses by a factor of 2 or more. It is, however, worth noting that the use of a Salpeter IMF with the upper and lower mass cutoffs as used here would not substantially change our masses relative to those of other galaxies at similar or lower redshifts as long as the IMF remains independent of redshift and galaxy mass.

It is presently difficult to estimate the combined effect of these potential systematic errors. The effects of changing the IMF to a more top-heavy one and using the intrinsically redder SED from the Maraston models would both be to lower the average stellar masses of the BBGs. The magnitude of the effect is unknown but could possibly be a factor of 2 or more.
6.2. Completeness

The $K_s$-selected sample is $\sim$82% complete at $K_{AB} \approx 23.5$ (§ 2). The $K_{AB}$ magnitudes for the BBG candidates range from 22.95 to 24.75. The brightest candidate is the X-ray–detected BBG 3348, with the second brightest BBG at $K_{AB} = 23.84$. The average magnitude is $K_{AB} = 24.2$. At this magnitude the completeness is $\sim$40% (Fig. 1). This represents the completeness, $\xi$, in selecting galaxies with $K$ magnitudes typical for our selected BBGs.

We also need to estimate the completeness in terms of stellar mass and age. We do this by using a model SED with a fixed observed $K_s$ magnitude of 24.2 for all redshifts. We use a model with solar metallicity, no internal extinction, and characterized by instantaneous star formation, i.e., $\tau = 0$. Furthermore, we use a maximally old stellar population; that is, at any given redshift, the stellar population is assumed to be as old as the universe at that particular epoch ($z_{\text{form}} = \infty$). At $z = 5$, a maximally old stellar population has an age of 1.2 Gyr, and at $z = 8.5$, the age is 0.6 Gyr. The stellar mass is derived in the same manner as for the BBG candidates: the $M_*/L_{\text{bol}}$ ratio is obtained from the BC03 model given the age of the stellar population, and the bolometric luminosity is obtained by integrating over the SED, normalized to an observed $K_{AB} = 24.2$. The resulting stellar mass as a function of redshift is shown in Figure 19 as a thick black line. The sawtooth appearance is due to the discrete age bins ($\Delta t = 100$ Myr) used for the models. Any galaxy with a younger stellar population, a more extended star formation history (i.e., $\tau > 0$), or lower metallicity would have a detection limit at a lower stellar mass. A higher metallicity and/or significant internal extinction, on the other hand, would increase the stellar mass needed for detection with $K_{AB} = 24.2$. In Figure 19 we also show the detection limits for a galaxy with a fixed age of 600 Myr and $Z = Z_\odot$ (dotted line) and one with a fixed age of 400 Myr and $Z = Z_\odot$ (dashed line). The other parameters ($E_{B-V} = 0.0$ and $\tau = 0$) are the same as for the maximally old stellar population. A maximally old stellar population of solar metallicity needs to have a mass $\geq 2 \times 10^{11} M_\odot$ at $z = 5$ and $\geq 9 \times 10^{11} M_\odot$ at $z = 7$ in order to be detected at $K_{AB} = 24.2$. The stellar mass needed for detection is lower if the age is less than the maximally old stellar population, as well as if some residual star formation is ongoing. To illustrate the latter point, we also show the detection limit for a stellar population of age 600 Myr and with an exponentially declining SFR with $\tau = 200$ Myr (dot-dashed line). In this case a $10^{11} M_\odot$ galaxy can be detected out to $z \sim 7.0$. The final conclusion from this exercise is that at $z \geq 5$ we can only detect galaxies more massive than a few times $10^{11} M_\odot$ if the stellar population is maximally old and passively evolving. For younger populations and if star formation is still ongoing (albeit at a much reduced level), we are sensitive to stellar masses from a few times $10^{10}$ to $10^{11} M_\odot$. Our best-fit masses for the $z \approx 5$ BBGs (Table 4) are in the range $\log (M_*/M_\odot) = 10.7$ to 11.7. The preceding analysis shows that at $\log (M_*/M_\odot) > 11.3$, even maximally old galaxies should have $K_s < 24.2$, and thus our photometric completeness estimate (40%) should be reasonable. However, we may be progressively more incomplete to old galaxies without ongoing star formation at masses $< 2 \times 10^{11} M_\odot$.

Without knowledge of the intrinsic properties characterizing the BBGs, it is difficult to define the volume over which we sample the galaxies given our selection criteria. The lower limit is of course set by our imposed selection of $z \geq 5$. For the upper redshift limit we use the mass limits depicted in Figure 19 to make a reasonable estimate based on the derived properties of the BBGs in our sample. As listed in Table 4, 6 of the 11 galaxies have a current SFR of at least a few solar masses per year, the average age of the stellar population is 0.8 $\pm$ 0.3 Gyr, and eight have $\tau > 0$. This suggests that we should use a less than maximally old stellar population, with a small amount of ongoing star formation, in defining the upper redshift limit. We therefore estimate the upper limit based on a stellar mass $\geq 10^{11} M_\odot$, age 0.6 Gyr, and a $\tau = 0.2$ Gyr, giving an ongoing SFR of $\sim 10 M_\odot$ yr$^{-1}$ and an upper redshift limit of $z = 7$ (Fig. 19). The comoving volume for the redshift interval $z = 5 - 7$, over the 145 arcmin$^2$ spanned by the GOODS-S field, is 7.0 x $10^5$ Mpc$^3$. The effective comoving volume can be expressed as $V_{\text{eff}} = 7.3 \times 10^5 \xi H$ Mpc$^3$, where $\xi$ is the completeness for detecting galaxies with observed $K_{AB} = 24.2$, estimated to $\xi = 0.4$, and $H$ represents the completeness when accounting for galaxies that may have dropped out of the selection for other reasons. To estimate a value for $H$ requires knowledge, or an educated guess, of the population of massive and evolved galaxies at these redshifts. We do not attempt this estimate here, but we do indicate when our ignorance of the completeness correction may affect the derived quantities. The effective comoving volume is $V_{\text{eff}} = 2.9 \times 10^5 H$ Mpc$^3$.

Assuming that all of the BBG candidates have correct redshift estimates, the comoving number density of massive and old galaxies at redshift $z = 5 - 7$ is $3.9 \times 10^{-5}$ $\xi^{-1} H^{-1}$ Mpc$^{-3}$. Adding the individual stellar masses, the total stellar mass becomes $2.3 \times 10^{12} M_\odot$, giving a stellar mass density of $8 \times 10^6 \eta^{-1} M_\odot$ Mpc$^{-3}$.

$9$ This represents the mean of the coverage of the J, H, and $K$ bands (156 and 124 arcmin$^2$, respectively; see § 2). It is slightly smaller than the GOODS ACS field (160 arcmin$^2$).
The corresponding values for the no-MIPS sample (see §4.4) are \(1.4 \times 10^{-5} \eta^{-1} \text{ Mpc}^{-3}\) and \(1.4 \times 10^{5} \eta^{-1} \text{ M}_\odot \text{ Mpc}^{-3}\), respectively.

Our Monte Carlo simulations (§3.3) allow us to estimate the fraction of the BBGs that have photometric redshifts \(z \geq 5\) when taking the photometric errors into consideration. In Figure 20 we show the combined probability distribution for photometric redshifts, as well as the corresponding stellar masses for the 11 Balmer break candidates. Each of the two distributions contains \(11 \times 10^5\) Monte Carlo realizations. The median redshift of the distribution is \(z_{\text{med}} = 5.2\), the same as the average of the best-fit solutions. The filled region corresponds to realizations with \(z \geq 5\) and makes up 67% of the Monte Carlo realizations. This suggests that our initial selection criterion of \(z \geq 5\) is fulfilled by \(\sim 65\% - 70\%\) of our candidates, although from the simulation data we cannot distinguish which ones. Hence, our estimate of 11 BBGs with \(z \geq 5\) needs to be corrected for this, leading to an estimate of seven to eight BBG candidates. The corresponding number density and stellar mass density should then be lowered by a corresponding factor \(2^{-7} \times 10^{-5} \eta^{-1} \text{ Mpc}^{-3}\) and \(5.4 \times 6^5 \text{ M}_\odot \text{ Mpc}^{-3}\), respectively). The caveat with this analysis is the presence of BBGs at redshifts \(z_{\text{phot}} < 5\), which may “spill over” into the \(z > 5\) range when the photometric errors are considered. A preliminary analysis of the number of Balmer break candidates in the redshift range \(4 \leq z_{\text{phot}} \leq 5\), based on a photometric redshift selection (T. Wiklind et al. 2008, in preparation), suggests that the number of BBG candidates at \(z \geq 5\) is \(\sim 10\), hence quite close to our initial estimate from the best-fit photometric redshifts. We therefore retain our number of 11 BBGs in the \(z = 5-7\) range.

7. DISCUSSION

The existence of massive and evolved galaxies at redshifts \(z \geq 5\), when the universe was \(\leq 1\) Gyr old, seems surprising at first sight. In the hierarchical scenario for galaxy formation, the majority of massive galaxies are assembled at relatively low redshifts. However, the presence of massive galaxies at high redshifts poses a fundamental problem for hierarchical models only if their number density exceeds that of correspondingly massive dark matter halos (e.g., Somerville 2004). In §6.2 we derived the number and mass density of the BBGs, using our sample of 11 galaxies, as well as for a more restricted sample only containing those candidates that are not detected with MIPS at 24 \(\mu\text{m}\), the no-MIPS sample.

By equating the comoving number density of the BBGs with the expected density of dark matter halos at the same redshift, we can estimate the maximum halo mass associated with the BBGs. Using the Sheth–Tormen modified Press–Schechter formalism (Sheth & Tormen 1999), with the dark matter halo concentration predicted for the revised value of the power spectrum normalization \(\sigma_8 = 0.74\) (Spergel et al. 2007) and the estimated lower limit to the number density of BBGs (3.9 \(\times 10^{-5} \eta^{-1} \text{ Mpc}^{-3}\)), we predict a halo mass of \(M_h = 1.0 \times 10^{12} \text{ M}_\odot\) (assuming the standard \(\Lambda \text{CDM}\) model). Using the average stellar mass for the BBGs, we get \(M_*/M_h \approx 0.20\). Considering the no-MIPS sample, with a number density \(1.4 \times 10^{-5} \eta^{-1} \text{ Mpc}^{-3}\), the corresponding halo mass is \(1.3 \times 10^{12} \text{ M}_\odot\), giving a ratio \(M_*/M_h \approx 0.08\). This estimate of the halo mass assumes that all available \(\sim 10^{12} \text{ M}_\odot\) halos at \(z \approx 5.2\) are associated with BBGs. If a fraction of these halos would host lower mass stellar systems, such as LBGs, the \(M_*/M_h\) ratio for the BBGs would have to increase accordingly.

The ratio of the baryonic to total mass can be expressed in terms of a star formation efficiency parameter \(\beta\) (\(M_* = \beta M_{\text{baryon}}\); the fraction of baryons turned into stars over the lifetime of the galaxy), and the stellar mass, \(M_*\), as

\[
M_{\text{baryon}}/M_{\text{total}} = \beta^{-1} M_*/M_{\text{total}} = \kappa,
\]

where \(M_{\text{total}} = \beta^{-1} M_* + M_h\). We can then write

\[
M_*/M_h = \beta \kappa / (1 - \kappa).
\]

Adopting \(\kappa = 0.17\) from the WMAP3 results (Spergel et al. 2007), we get \(M_*/M_h = 0.20\beta\). Klypin et al. (2002) estimate the total (virial) and baryonic mass of the Milky Way and M31 galaxies and find \(M_*/M_h = 0.06 - 0.08\), implying that in this case

\[10\]
\(\beta = 0.3-0.4\). For the BBGs, we find \(\beta \approx 0.4-1.0\), where the lower value corresponds to the no-MIPS sample. If we only consider the no-MIPS sample, the baryonic fraction is comparable to local galaxies. However, for the full sample, the results suggest that the BBGs at \(z \approx 5.2\) contain a higher fraction of baryons than galaxies at \(z \approx 0\). Another possible explanation for the high baryonic fraction is that the number density of dark matter halos at high redshift is underestimated by the Sheth-Tormen analysis, or that we have systematically overestimated the stellar masses of the BBGs by a factor \(\approx 2\). Using a Chabrier or Kroupa IMF with a less steep low-mass end could lower the estimated stellar masses by a factor of \(1.5-1.8\) (see § 6.1).

It would be more instructive to compare the \(M_*/M_h\) ratio to that of massive elliptical galaxies at \(z \approx 0\). However, the evidence for dark matter in elliptical galaxies is still circumstantial and limited to the central regions. Using planetary nebulae and globular clusters as kinematic probes, it has been possible to push the analysis to \(\sim 5 R_{\text{eff}}\) (e.g., Romanowsky et al. 2003; Richtler et al. 2004). While the number of ellipticals studied in detail is still small, the general conclusion is that most have surprisingly weak dark matter halos, i.e., large \(M_*/M_h\) ratios. It remains to be determined whether the inferred \(M_*/M_h\) ratio for BBGs is consistent with local giant elliptical galaxies.

The stellar mass density of the universe from redshifts 0 to 6 has been estimated by several groups, using different samples and methods (e.g., Bell et al. 2003; Dickinson et al. 2003a; Rudnick et al. 2003, 2006; Fontana et al. 2006; Yan et al. 2006). Some of these results are listed in Table 7, as a comparison with the results obtained for the BBGs. Most of the values listed in Table 7 are based only on the observed objects and are lower limits. In a few cases, the mass function has been integrated to obtain the total stellar mass (e.g., Dickinson et al. 2003a). In the local universe, the global stellar mass density is \((3-4) \times 10^8 M_\odot \, \text{Mpc}^{-3}\), while it decreases to \(\sim 0.3 \times 10^8 M_\odot \, \text{Mpc}^{-3}\) at \(z = 2.5-3\). In § 6.2 we found that the stellar mass density of the 11 BBG candidates is \(8 \times 10^5 \, \eta^{-1} M_\odot \, \text{Mpc}^{-3}\). This is \(\sim 2\%-3\%\) of the present-day total stellar mass density. Restricting the comparison to large early-type galaxies in the local universe, that is, galaxies at least as massive as our BBG sample, the percentage increases to \(\sim 4\%-6\%\). Comparing with the stellar mass density at \(z = 2\), the BBG sample already comprises \(20\%-25\%\) of the total stellar mass found at this redshift. For the no-MIPS sample, the stellar mass density is \(\sim 5\) times smaller, and in this case the comparison with stellar mass densities at lower redshifts has to be corrected accordingly.

The galaxies found in this study are remarkable in that they contain a large stellar mass, have small physical sizes, and their main epoch of star formation occurred at \(z \gtrsim 10\). Galaxies with similar properties have, however, also been found by others. In a recent paper, McClure et al. (2006) searched for LBGs in the UKIDSS ultradepth survey and found nine candidates with \(z > 5\). Their stellar masses are \(>5 \times 10^{10} M_\odot\), and their ages range from 50 to 500 Myr. Overall, these galaxies have properties similar to our BBGs. The number density for the \(z > 5\) galaxies found by McClure et al. (2006) is \(\sim 4\) times smaller than what we find in this paper. However, the different selection process, the fact that the UKIDSS sample does not include IRAC data, and the large completeness corrections needed make a comparison difficult. A number of massive galaxies at \(z > 4\) were also found by Fontana et al. (2006) using the GOODS-MUSIC sample. Their broadband photometric data set consists of 14 bands, including the four IRAC bands. The objects were identified by fitting template SEDs based on BC03 models to all galaxies in the sample. The best-fitting SEDs for the high-redshift objects suggest that they are passively evolving galaxies, characterized by a very short timescale for star formation or by a constant star formation and a large amount of dust extinction. The stellar masses found are in excess of \(10^{11} M_\odot\). Hence, massive and passively evolving galaxies at \(z > 5\) are found in several studies. A direct comparison of the results is presently not practical as different selection criteria are used, and the completeness corrections are presently poorly defined.

Another surprising property of the BBGs is their compact sizes. As derived in § 4.3, the typical half-light radius is \(\lesssim 2\) kpc. Although this is larger than what is expected from the size versus redshift relation derived for UV-bright galaxies at similarly high redshift (Ferguson et al. 2004; Bouwens et al. 2004; T. Dahlen et al. 2008, in preparation), the stellar masses of the BBGs are at least 10 times higher. No massive compact galaxies of this type have been found in the local universe. However, compact galaxies with a large stellar mass have been found at \(z \sim 1.4\) (Trujillo et al. 2006) and at \(z \sim 2.5\) (Daddi et al. 2005a; Zirm et al. 2007; Toft et al. 2007). These galaxies are massive \((M_\odot \gtrsim 10^{11} M_\odot)\), with no sign of AGN activity, and contain a passively evolving stellar population, similar to the BBGs. The effective radii of these galaxies, measured at rest-frame optical wavelengths, are typically \(\lesssim 1\) kpc (Zirm et al. 2007; Toft et al. 2007), or 3–6 times smaller than local counterparts of similar stellar mass. It is hypothesized that the onset of rapid star formation in these systems quenches the star formation process, leading to very compact objects. These galaxies, as well as the BBGs, cannot represent fully assembled systems and must undergo subsequent evolution in their structural parameters in order to resemble local galaxies with the same stellar mass.

The presence of a population of massive galaxies that underwent a period of intense star formation at \(z \sim 10-25\) is likely to have ramifications for the reionization of the IGM. Panagia et al. (2005) calculated that the star formation associated with the formation of the massive \(z = 6.5\) galaxy HUDF-JD2 (Mobasher et al. 2005) could significantly contribute to the reionization of the IGM. The main uncertainties were the escape fraction of the Lyman continuum photons and the volume density of objects similar to JD2. With the new sample of poststarburst galaxies with formation redshifts in the same range as JD2, it is possible to address this question. The integrated output of Lyman continuum photons from the Balmer break candidates depends only on the total stellar mass and the assumed IMF (Panagia et al. 2005).

### Table 7: Stellar Mass Densities

| Redshift | \(\log(\rho_*/M_\odot \, \text{Mpc}^{-3})\) | Reference |
|----------|--------------------------------|-----------|
| 0.0..............| 8.60 | Bell et al. (2003) |
| 0.1.............| 8.59\pm0.04 | Rudnick et al. (2006) |
| 0.5-1.4..........| 8.46\pm0.04 | Dickinson et al. (2003a) |
| 2.0.............| 7.48\pm0.12 | Rudnick et al. (2003) |
| 2.0-2.5...........| 7.58\pm0.11 | Dickinson et al. (2003a) |
| 2.5.............| 7.60\pm0.04 | Fontana et al. (2006) |
| 2.5-3.0...........| 7.52\pm0.11 | Dickinson et al. (2003a) |
| 2.8.............| 7.59\pm0.10 | Rudnick et al. (2006) |
| 5.0.............| 7.23\pm0.12 | Fontana et al. (2006) |
| 5.2\pm0.5........| \(>6.90\)\(=6.15\)^a | This paper |
| 6.0..............| \(>6.78\) | Stark et al. (2007) |

Note.—Not a complete sample of mass density estimates (for further references see Rudnick et al. 2006).

^a No-MIPS sample.
Because the average stellar mass for the BBG candidates is about a factor of 2 smaller than for JD2, assuming the same IMF, the average number of Lyman continuum photons is likewise a factor of 2 lower. Panagia et al. (2005) concluded that if each field of 2.5′ × 2.5′ contained a source like JD2, then these sources account for at least ~20% of the reionization of the IGM. A higher percentage is possible if the escape fraction is higher and/or the IGM is clumped. In the present case, we have a total area that is 25 times larger and a total ionizing photon output ~10 times larger than in the case of JD2. Hence, the implication is that the BBG sources can account for ~10% or more of the photons needed for reionization, depending on the poorly constrained parameters describing the Lyman continuum escape fraction and the clumpiness of the IGM itself. The implications for reionization are discussed in more detail in N. Panagia et al. (2008, in preparation).

8. SUMMARY

In this paper we present evidence for a population of very massive and evolved galaxies at z ≥ 5. The results have been obtained by combining HST ACS, VLT ISAAC, and Spitzer IRAC broadband photometric data on the GOODS-S field.

Our main results are as follows:

1. Using the $K_s - 3.6 \mu$m color index as the primary diagnostic for identifying evolved stellar systems at z ≥ 5, and using additional colors (both $J - K$ and $H - 3.6 \mu$m) to aid the separation of high-redshift candidates from lower redshift interlopers, we defined a sample of 134 potential candidates. Fitting BC03 models to the candidates, allowing for an extended parameter space including redshift, age, internal extinction, metallicity, and star formation history, we extract 11 galaxies that are at redshift z ≥ 5. The confidence limits of the fitted parameters are tested through Monte Carlo simulations, where the photometry is allowed to vary stochastically within their formal errors. One of the candidates has a spectroscopically confirmed redshift agreeing with our photometric estimate.

2. The 11 candidates have an average stellar mass of $2 \times 10^{11} M_{\odot}$, ages of 0.2–1.0 Gyr, and subsolar to solar metallicities. Most of the candidates only have small amounts of dust obscuration and low levels of ongoing star formation. One of the candidates is detected in X-rays with Chandra. The X-ray luminosity is ~0.2% of the bolometric luminosity. The formation redshift of the candidate galaxies ranges from $z_{\text{form}} = 6$ to $z_{\text{form}} ≥ 25$. The completeness of our sample is estimated to be ~40% based on the $K_s$ selection only. However, we may be progressively more incomplete to old galaxies without ongoing star formation at masses $< 2 \times 10^{11} M_{\odot}$.

3. Seven of the 11 BBG candidates are detected in the MIPS 24 μm band, including one X-ray–detected source. The high detection rate is surprising given the large redshift implied by the model fits and the low level of ongoing star formation. While the 24 μm detections could indicate PAH emission for galaxies at $z \sim 2–3$, they are also consistent with a dust-obscured AGN at $z \sim 5$. We note that for the $z \geq 5$ solutions, six of the seven MIPS-detected BBGs have significant internal extinction, while the galaxies in the non-MIPS sample appear to be essentially dust-free. The only exceptions are BBG 3348, which is the only X-ray–detected BBG, and BBG 3179 (JD2), the highest redshift source.

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